HYDRAULIC DESIGN CRITERIA

SHEETS 610-1 to 610-7

TRAPEZOIDAL CHANNELS

1. Hydraulic Design Charts 610-1 to 610-7 are design aids for reducing the computation effort in the design of trapezoidal channels having various side slopes from 1 to 1 to 3 to 1 with uniform subcritical or supercritical flow. It is expected that the charts will be of value in preliminary design work where different channel sizes, roughness values, and slopes are to be investigated. Certain features of the charts were based on graphs prepared by the Los Angeles District, CE. Charts 610-1 to 610-7 can be used to interpolate values for intermediate side slopes.

2. Basic Equations. Manning's formula for open channel flow,

$$Q = \frac{1.486\ A\ S^{1/2}\ R^{2/3}}{n}$$

can be separated into a factor, involving slope and friction

$$C_n = \frac{1.486\ S^{1/2}}{n}$$

and a geometric factor involving area and hydraulic radius

$$C_k = AR^{2/3}\ .$$

Chart 610-1 and -1/1 show values of the factor, C_n , for slopes of 0.0001 to 1.0 and n values of 0.010 to 0.035. Charts 610-2 to -4/1-1 show values of the geometric factor, C_k , for base widths of 0 to 600 ft and depths of 2 to 30 ft. Charts 610-5 to -7 show values of critical depth divided by the base width for discharges of 1,000 to 200,000 cfs and base widths of 4 to 600 ft.

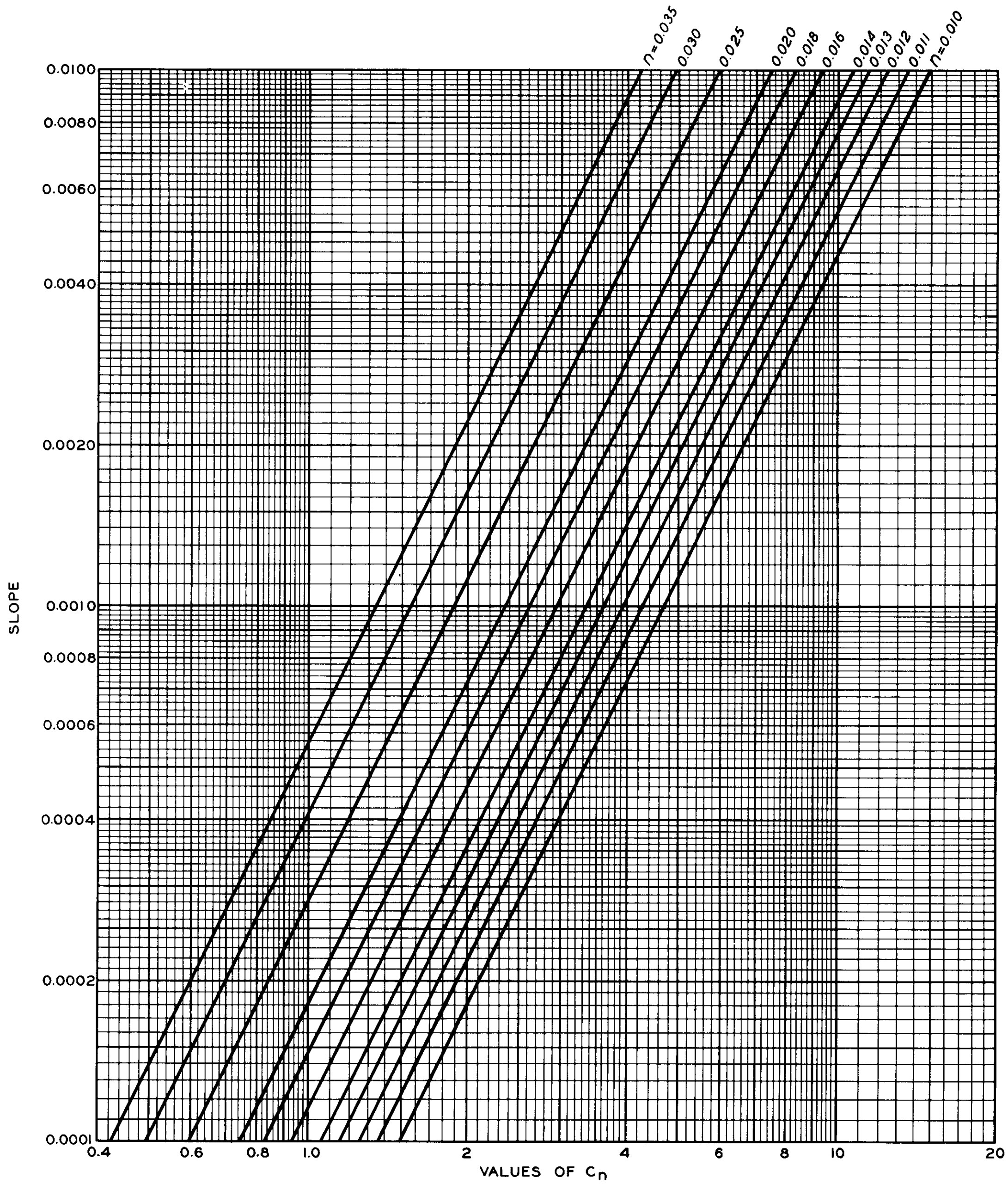
3. Application. Preliminary design of trapezoidal channels for subcritical or supercritical flow is readily determined by use of the charts in the following manner:

a. With given values of n and S , C_n can be obtained from charts 610-1 and -1/1.

b. Since $Q = C_n C_k$ the required value of C_k can be obtained by dividing the design Q by C_n .

c. With the required C_k value, suitable channel dimensions can be selected from charts 610-2 to -4/1-1.

d. Charts 610-5 to 610-7 can be used to determine the relation of design depth to critical depth.



FORMULA:

$$C_n = \frac{1.486\, S^{\frac{1}{2}}}{n}$$

WHERE:
S = SLOPE
n = MANNING'S "n"

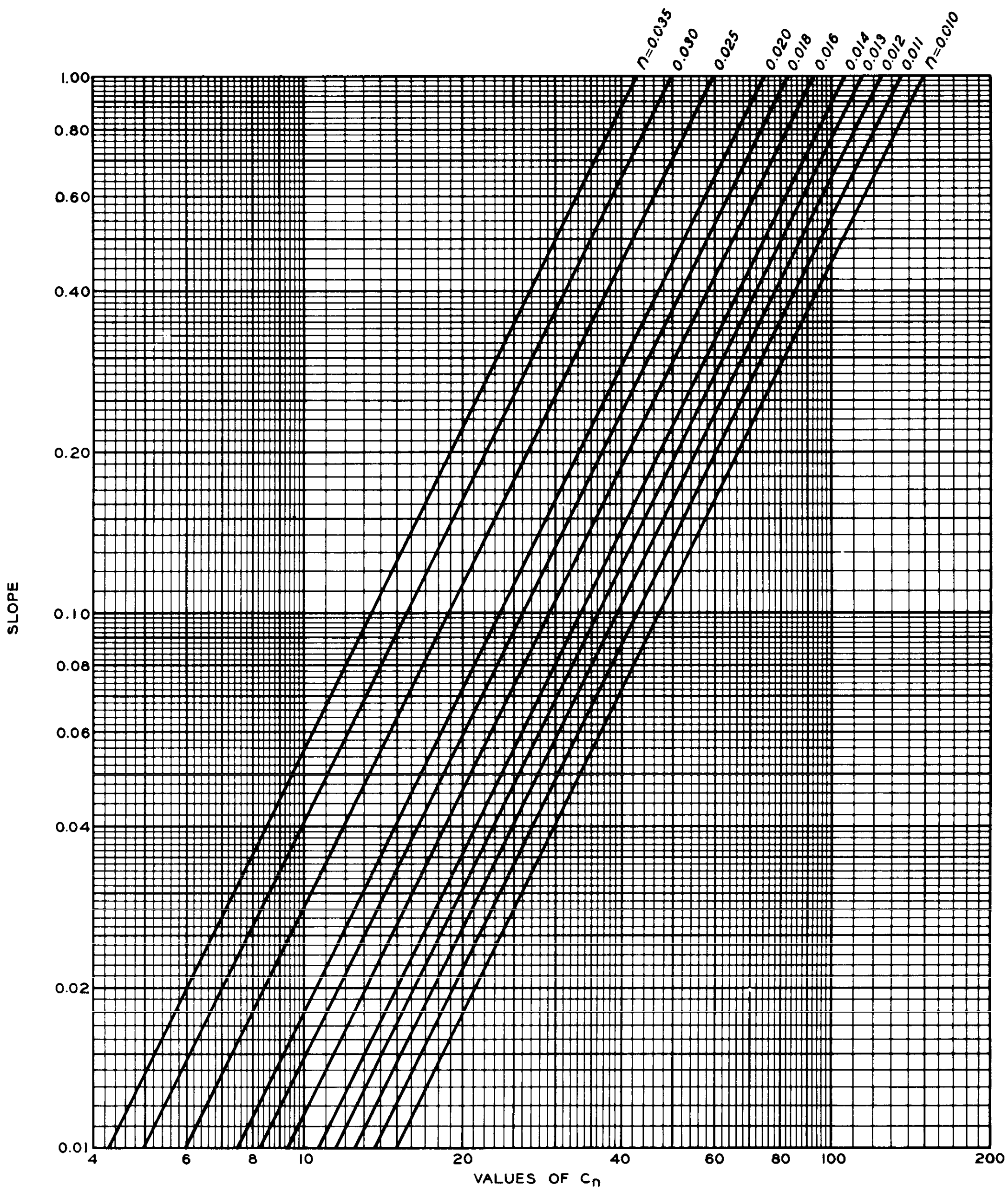
OPEN CHANNEL FLOW

SLOPE COEFFICIENTS

0.0001 < S < 0.010

HYDRAULIC DESIGN CHART 610-1

REVISED 8-58 WES 2-54



FORMULA:

$$C_n = \frac{1.486\,S^{\frac{1}{2}}}{n}$$

WHERE:
S = SLOPE
n = MANNING'S "n"

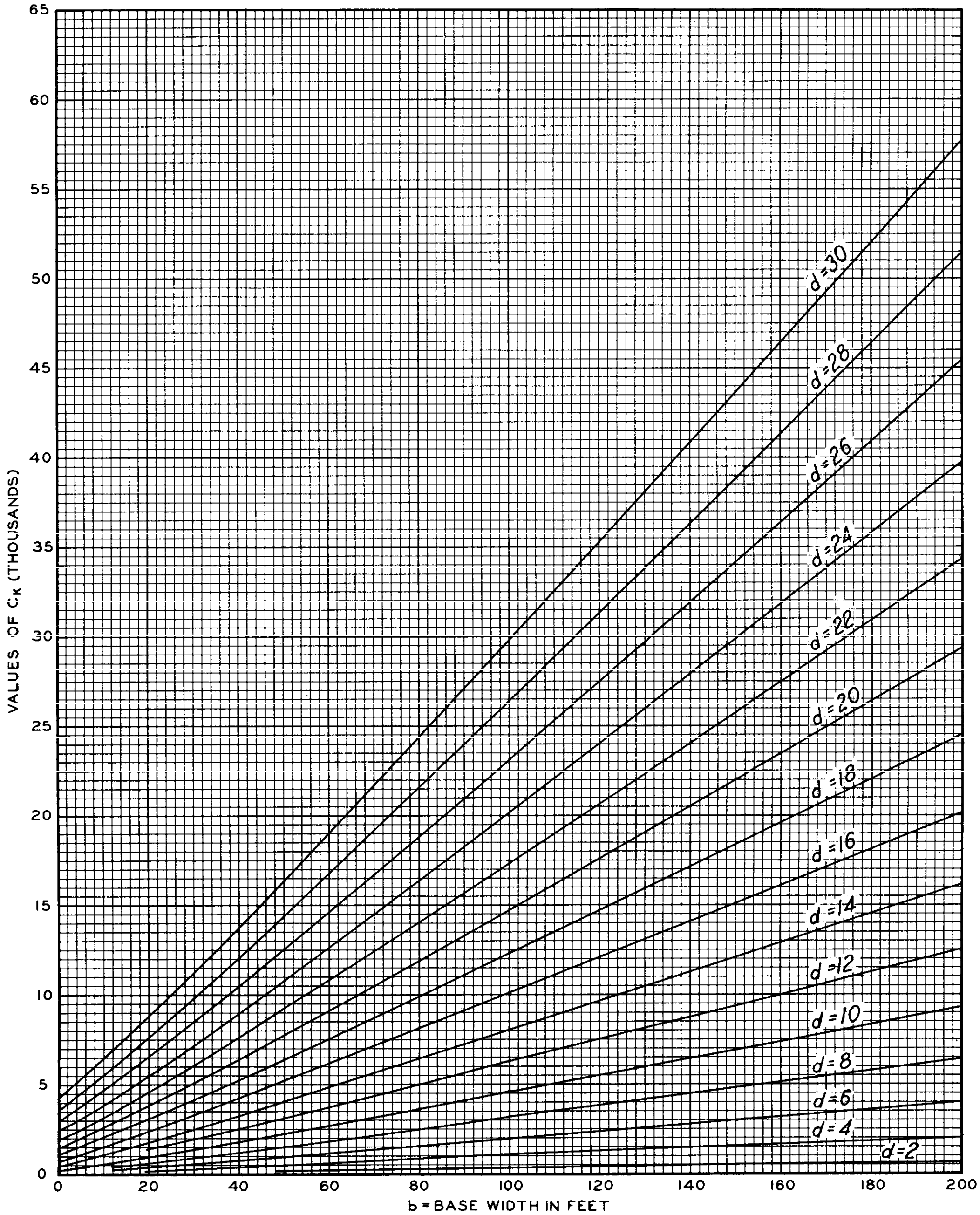
OPEN CHANNEL FLOW

SLOPE COEFFICIENTS

0.01 < S < 1.00

HYDRAULIC DESIGN CHART 610-1/1

REVISED 8-58 WES 2-54

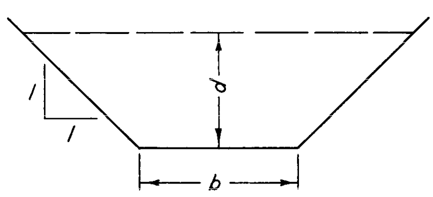


$C_K = AR^{2/3}$

WHERE:

A = AREA

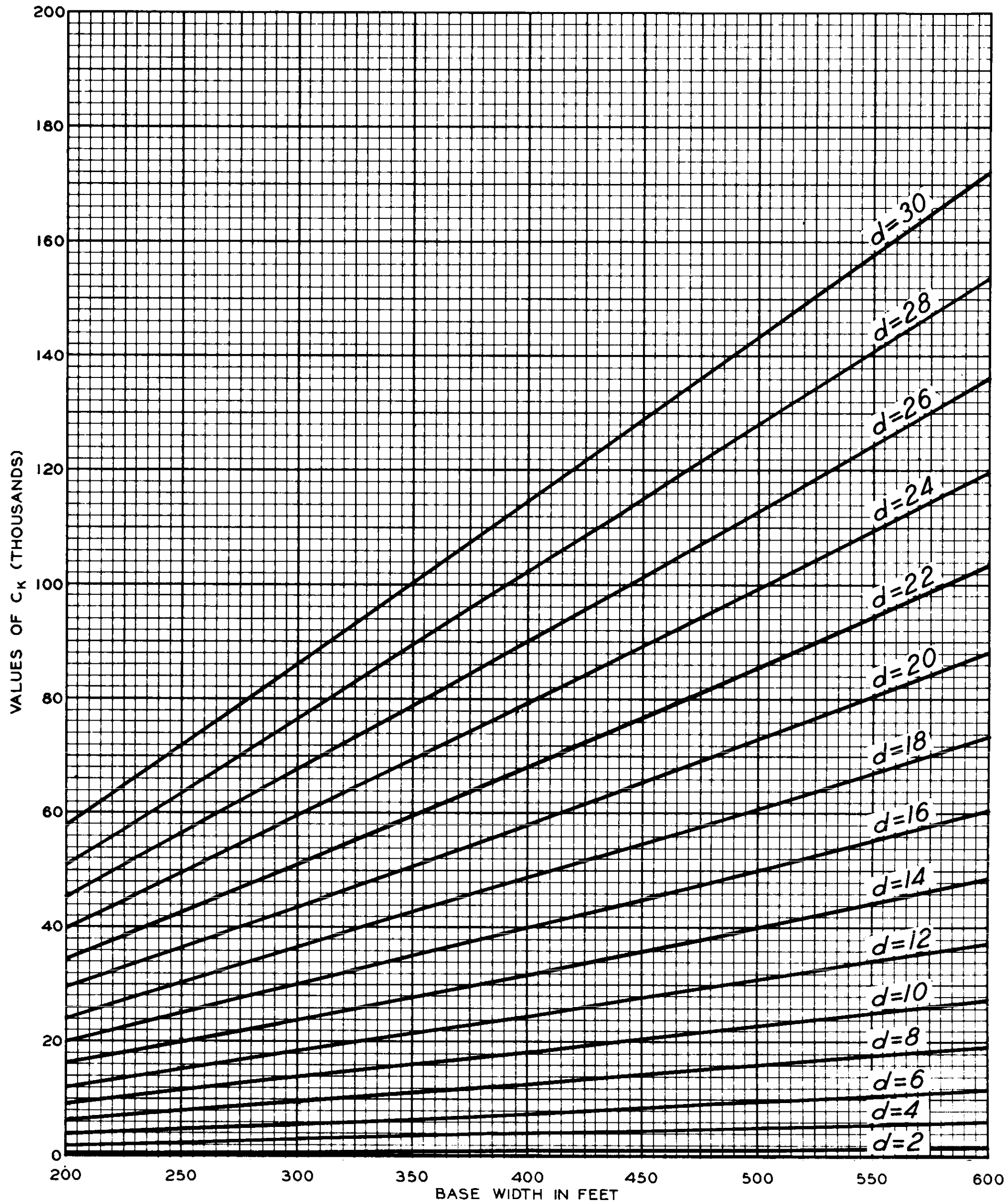
R = HYDRAULIC RADIUS



TRAPEZOIDAL CHANNELS
C_K VS BASE WIDTH
SIDE SLOPE 1 TO 1

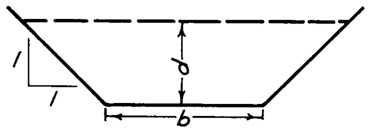
HYDRAULIC DESIGN CHART 610-2

WES 2-54



$C_K = AR^{2/3}$

WHERE:
A=AREA
R=HYDRAULIC RADIUS

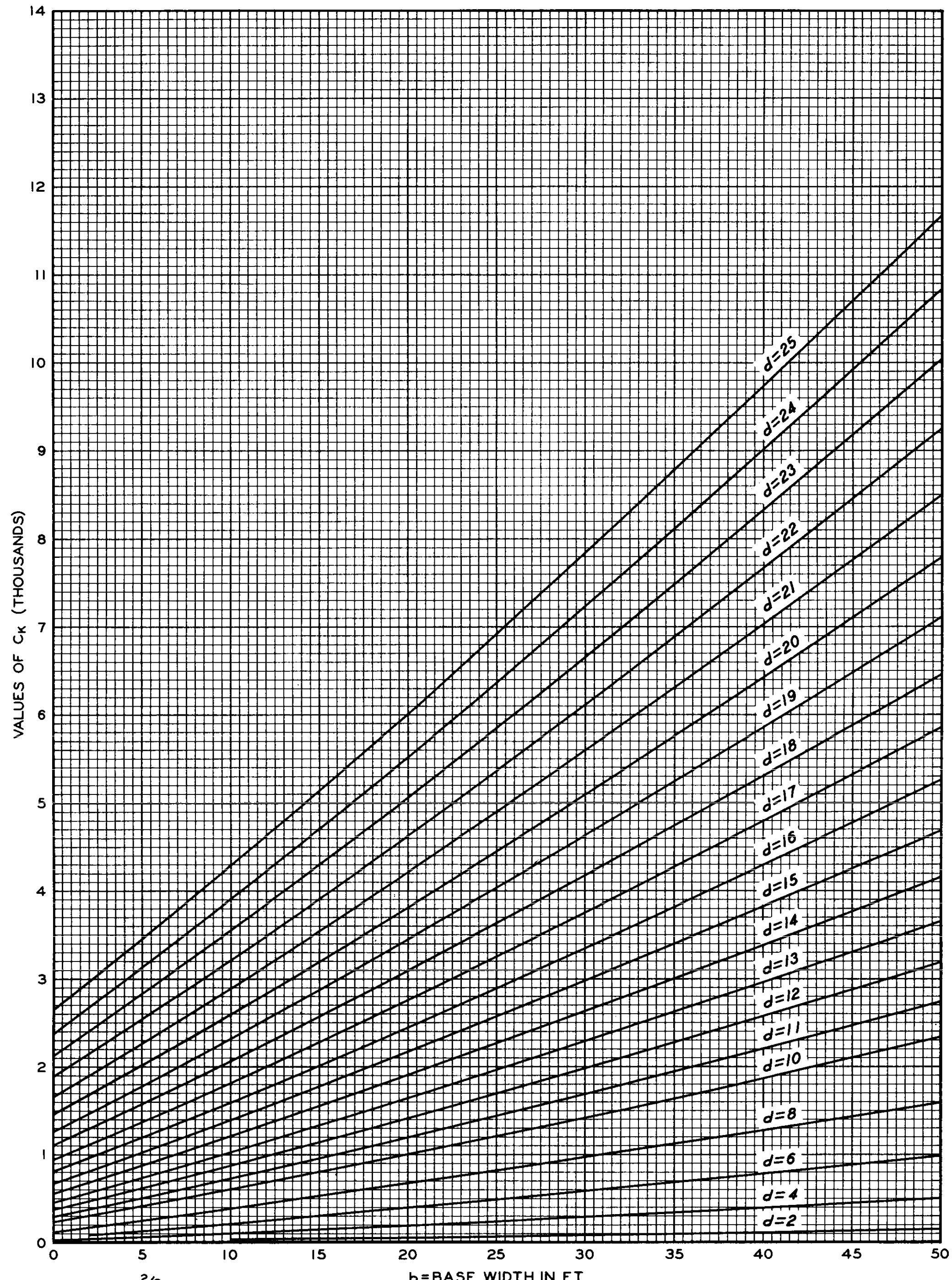


TRAPEZOIDAL CHANNELS C_K VS BASE WIDTH

SIDE SLOPE 1 TO 1

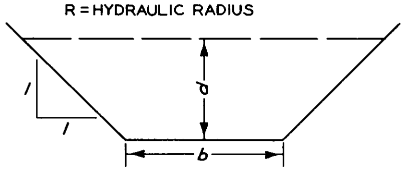
HYDRAULIC DESIGN CHART 610-2/1

WES 9-54



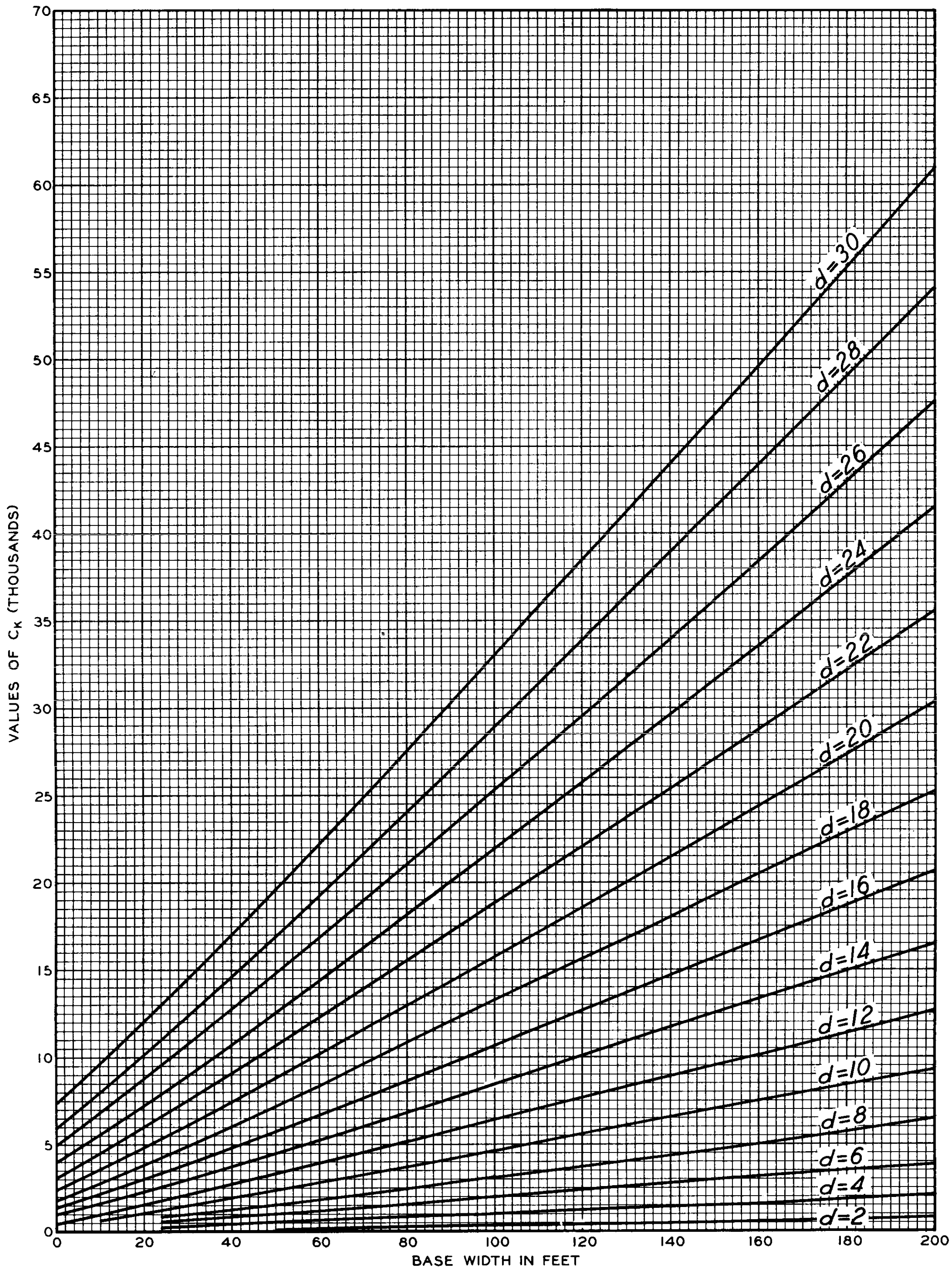
$C_K = AR^{2/3}$

WHERE:
A = AREA
R = HYDRAULIC RADIUS



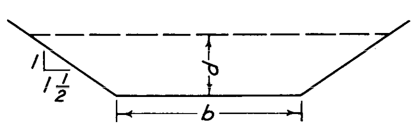
TRAPEZOIDAL CHANNELS
C_K VS BASE WIDTH
SIDE SLOPE 1 TO 1
BASE WIDTH 0 TO 50 FEET

HYDRAULIC DESIGN CHART 610-2/1-1



$C_K = AR^{2/3}$

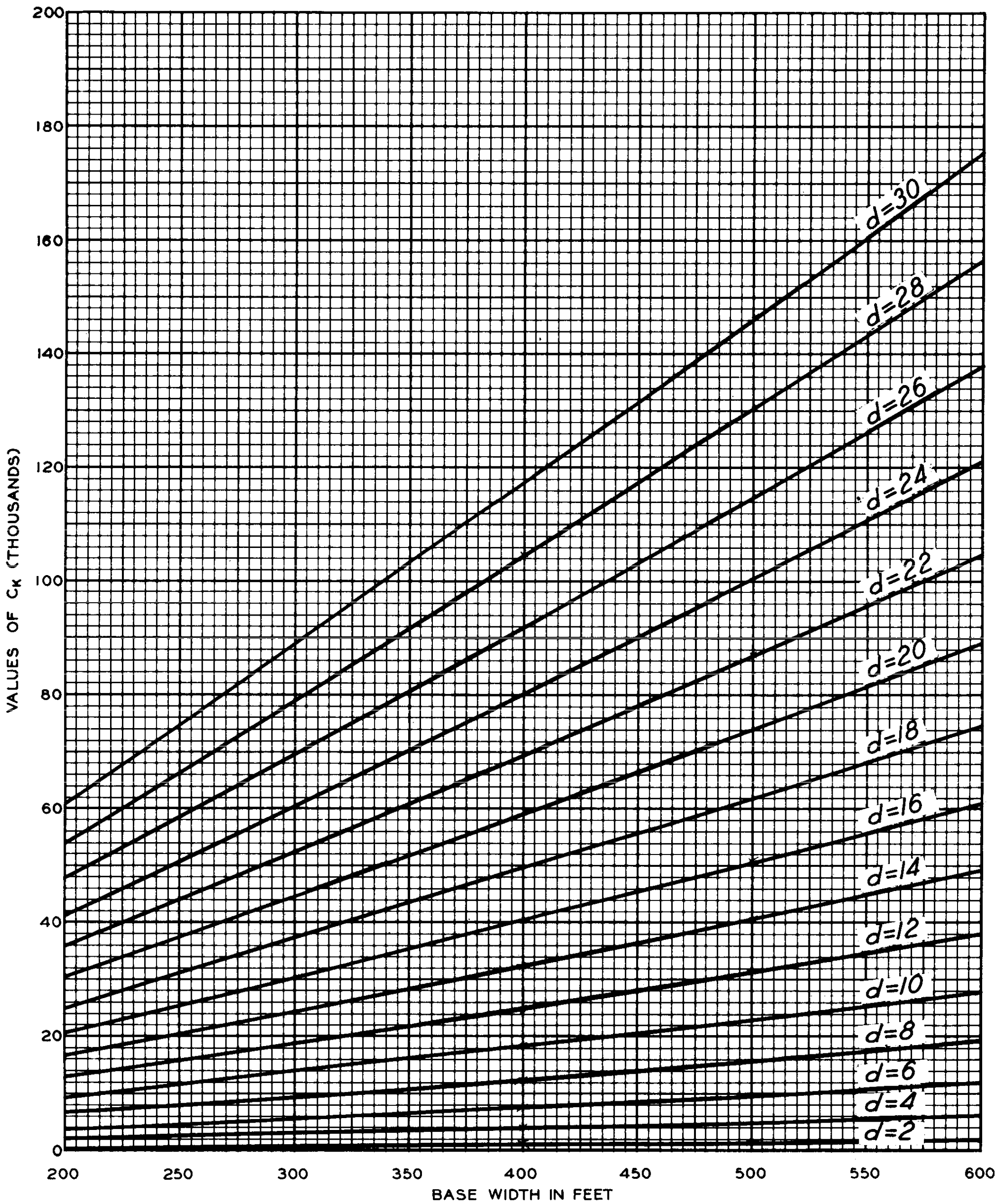
WHERE:
A = AREA
R = HYDRAULIC RADIUS



TRAPEZOIDAL CHANNELS
C_K VS BASE WIDTH
SIDE SLOPE $1\frac{1}{2}$ TO 1

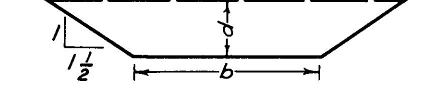
HYDRAULIC DESIGN CHART 610-2/2

WES 9-54



$C_K = AR^{2/3}$

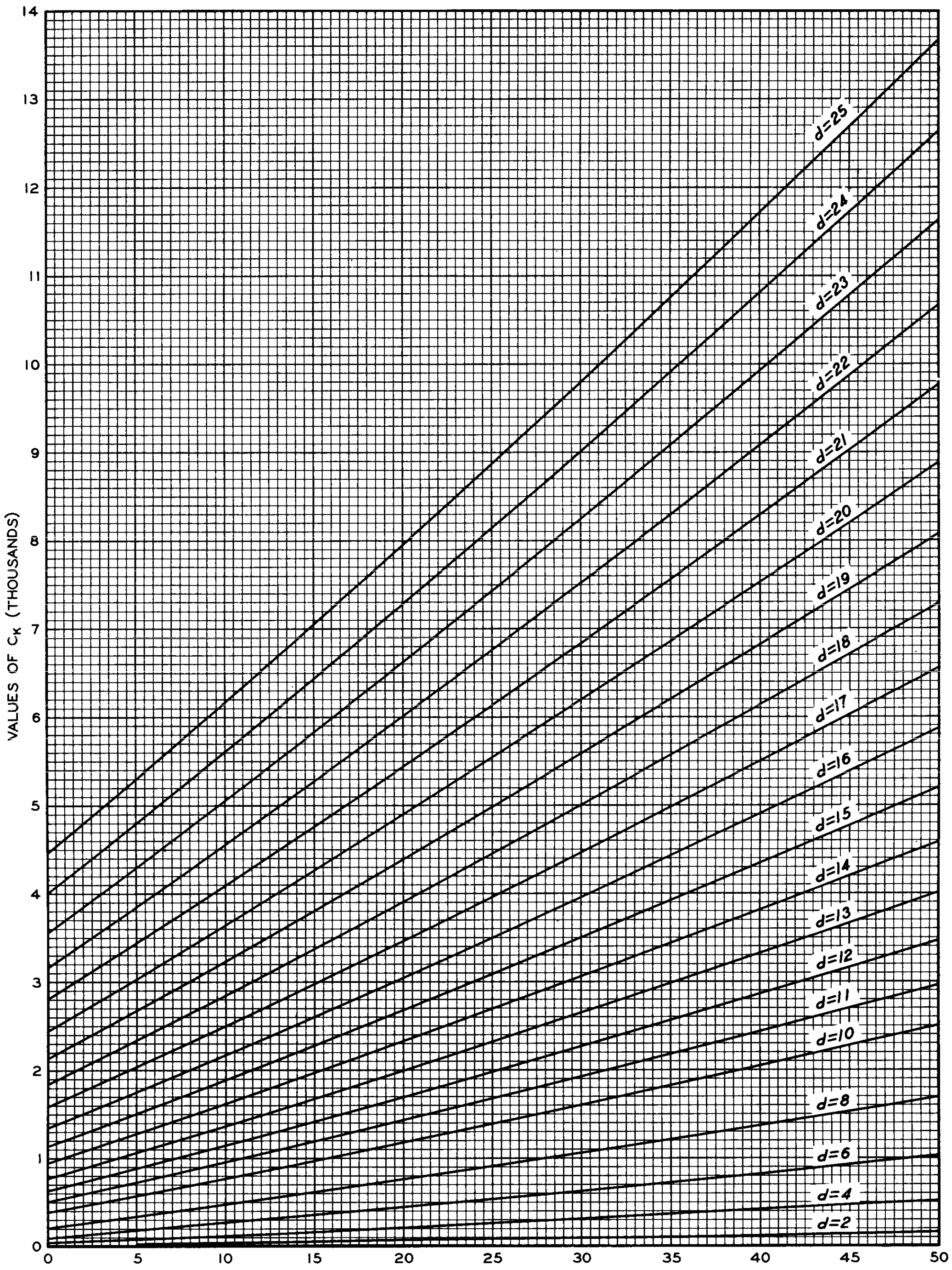
WHERE:
A=AREA
R=HYDRAULIC RADIUS



TPAPEZOIDAL CHANNELS
C_K VS BASE WIDTH
SIDE SLOPE $1\frac{1}{2}$ TO 1

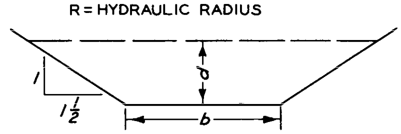
HYDRAULIC DESIGN CHART 610-2/3

WES 9-54



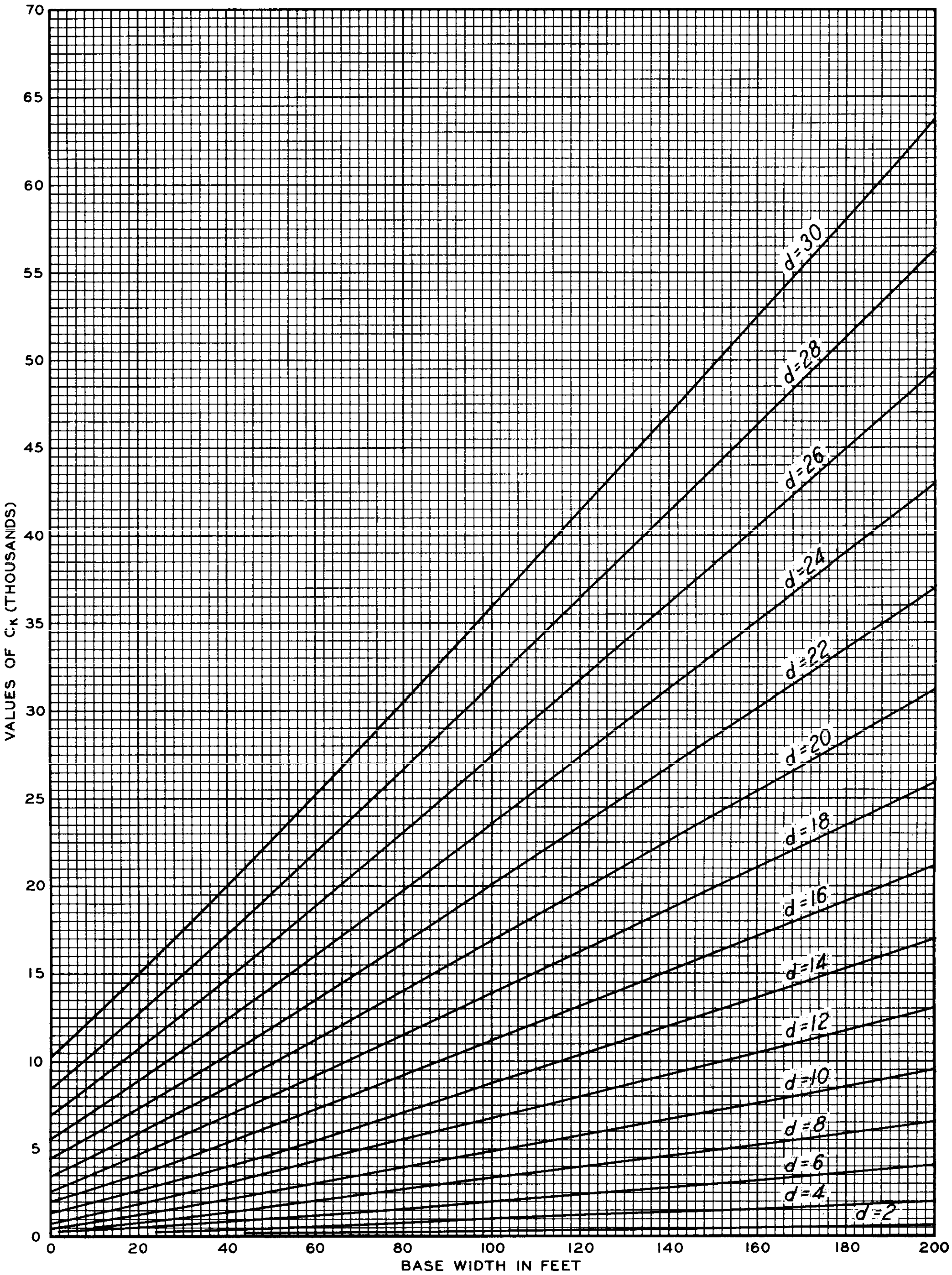
$C_K = AR^{2/3}$

WHERE:
A = AREA
R = HYDRAULIC RADIUS



TRAPEZOIDAL CHANNELS
C_K VS BASE WIDTH
SIDE SLOPE $1\frac{1}{2}$ TO 1
BASE WIDTH 0 TO 50 FEET

HYDRAULIC DESIGN CHART 610-2/3-1

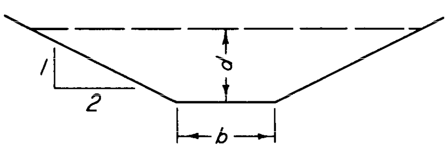


$C_K = AR^{2/3}$

WHERE:

A = AREA

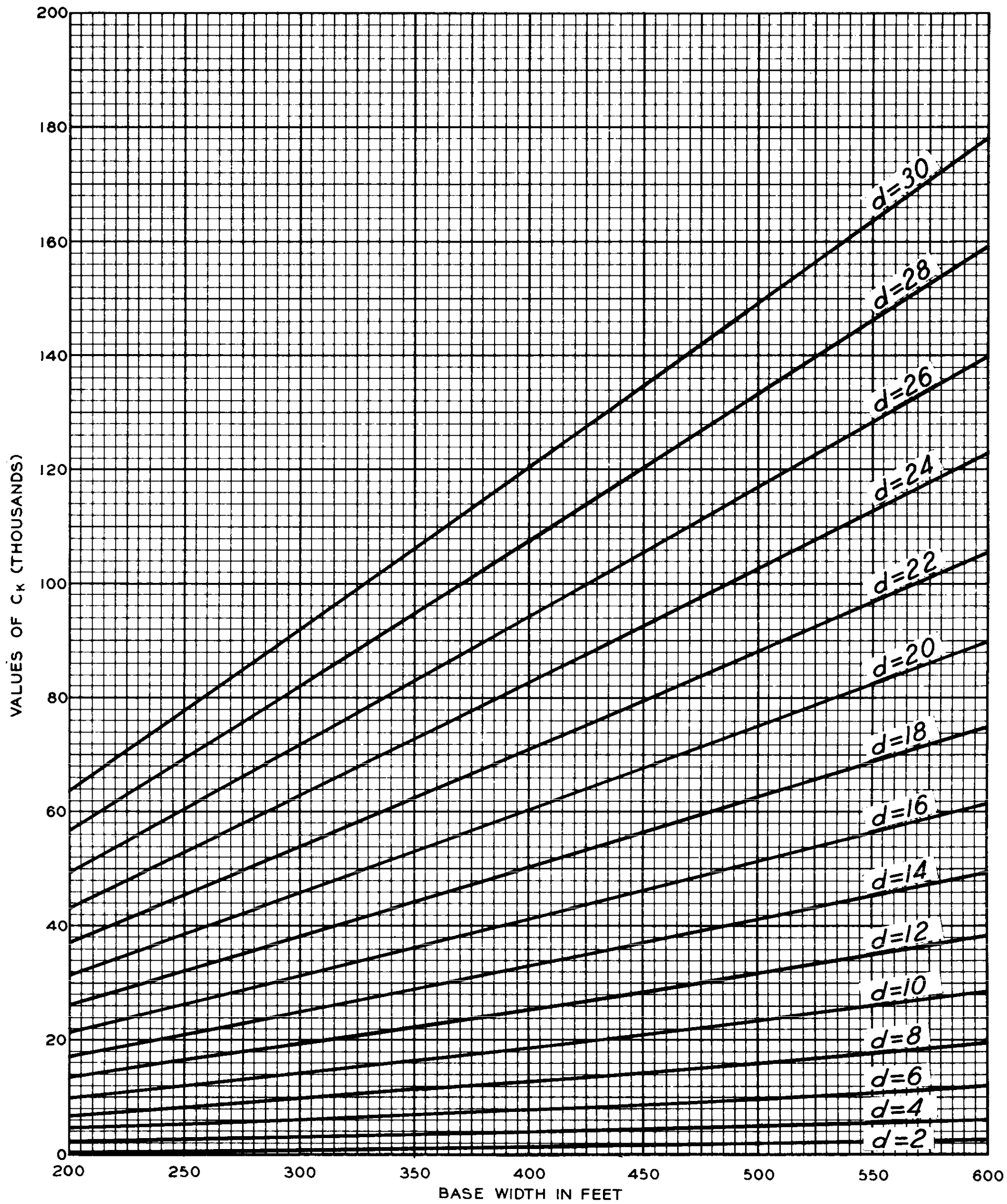
R = HYDRAULIC RADIUS



TRAPEZOIDAL CHANNELS
C_K VS BASE WIDTH
SIDE SLOPE 2 TO 1

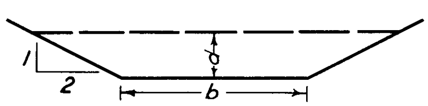
HYDRAULIC DESIGN CHART 610-3

WES 2-54



$C_K = AR^{2/3}$

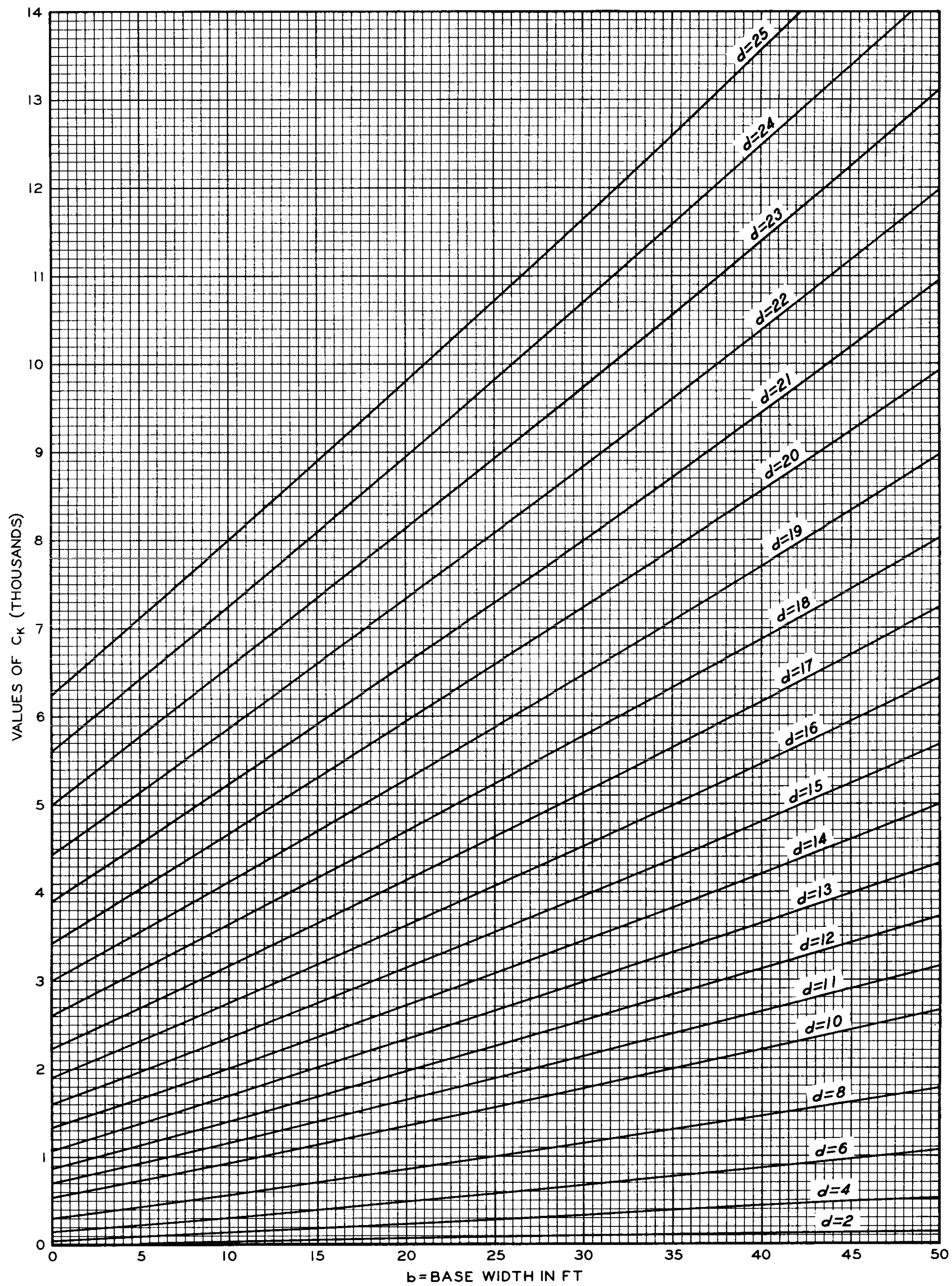
WHERE:
A=AREA
R=HYDRAULIC RADIUS



TRAPEZOIDAL CHANNELS
C_K VS BASE WIDTH
SIDE SLOPE 2 TO 1

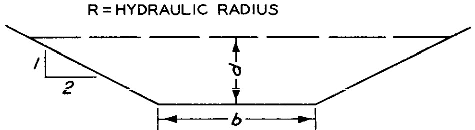
HYDRAULIC DESIGN CHART 610-3/1

WES 9-54



$C_K = AR^{2/3}$

WHERE:
A = AREA
R = HYDRAULIC RADIUS

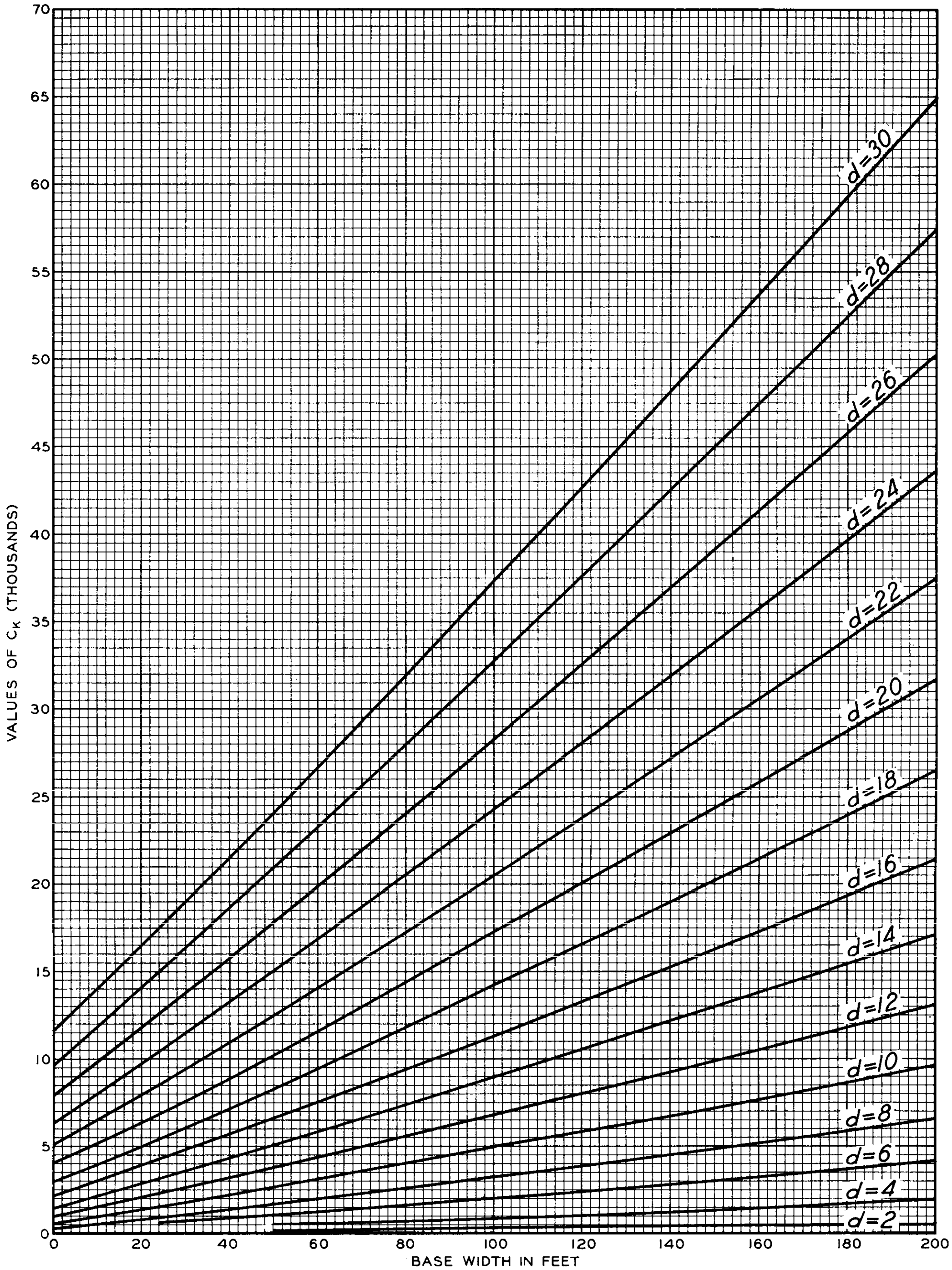


TRAPEZOIDAL CHANNELS
C_K VS BASE WIDTH
SIDE SLOPE 2 TO 1
BASE WIDTH 0 TO 50 FEET

HYDRAULIC DESIGN CHART 610-3/1-1

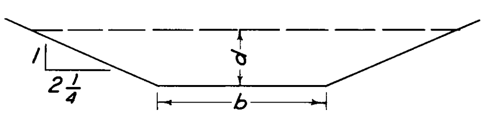
PREPARED BY U. S. ARMY ENGINEER WATERWAYS EXPERIMENT STATION, VICKSBURG, MISSISSIPPI

WES 5-59



$C_K = AR^{2/3}$

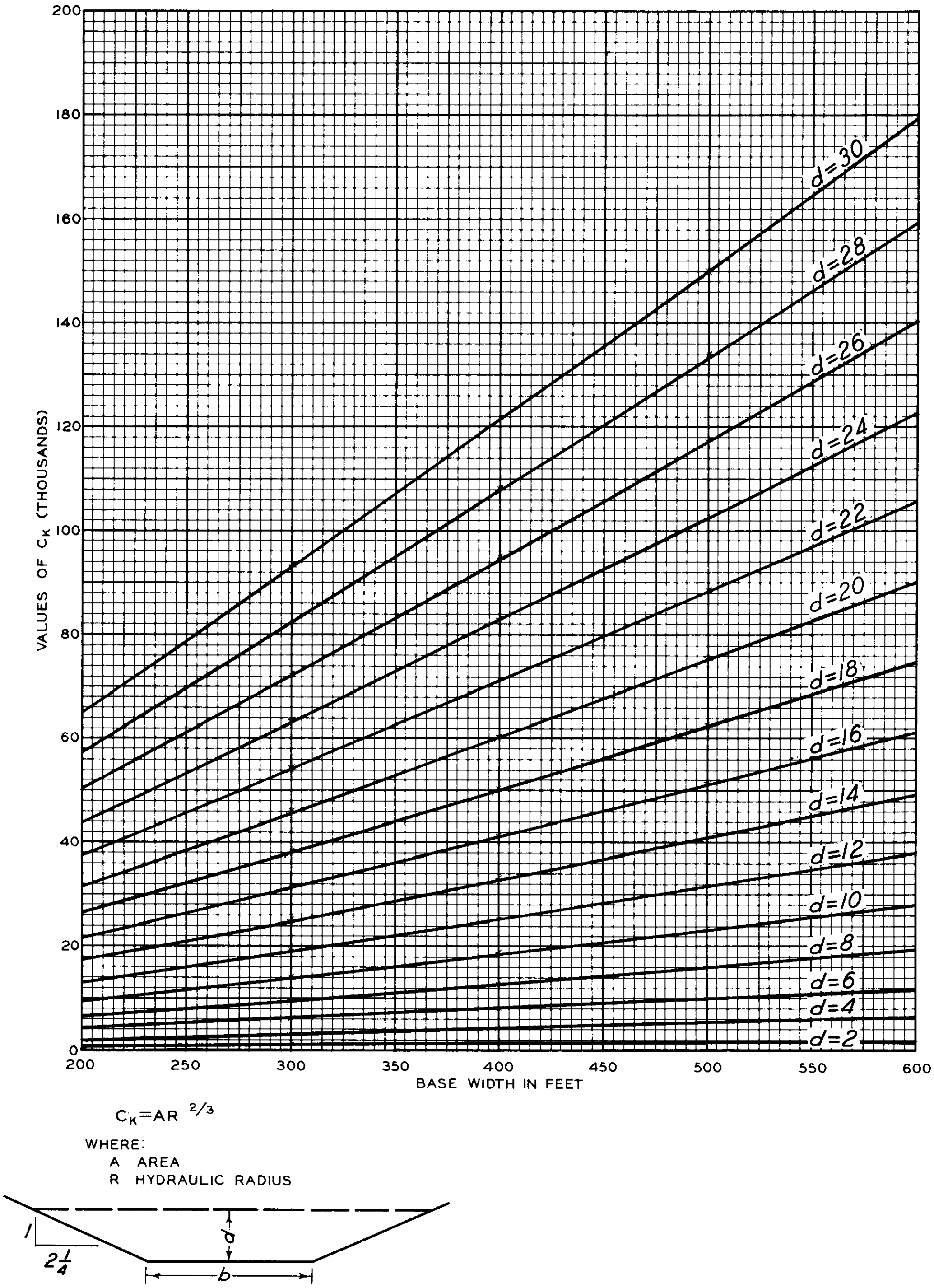
WHERE:
A = AREA
R = HYDRAULIC RADIUS



TRAPEZOIDAL CHANNELS
C_K VS BASE WIDTH
SIDE SLOPE $2\frac{1}{4}$ TO 1

HYDRAULIC DESIGN CHART 610-3/2

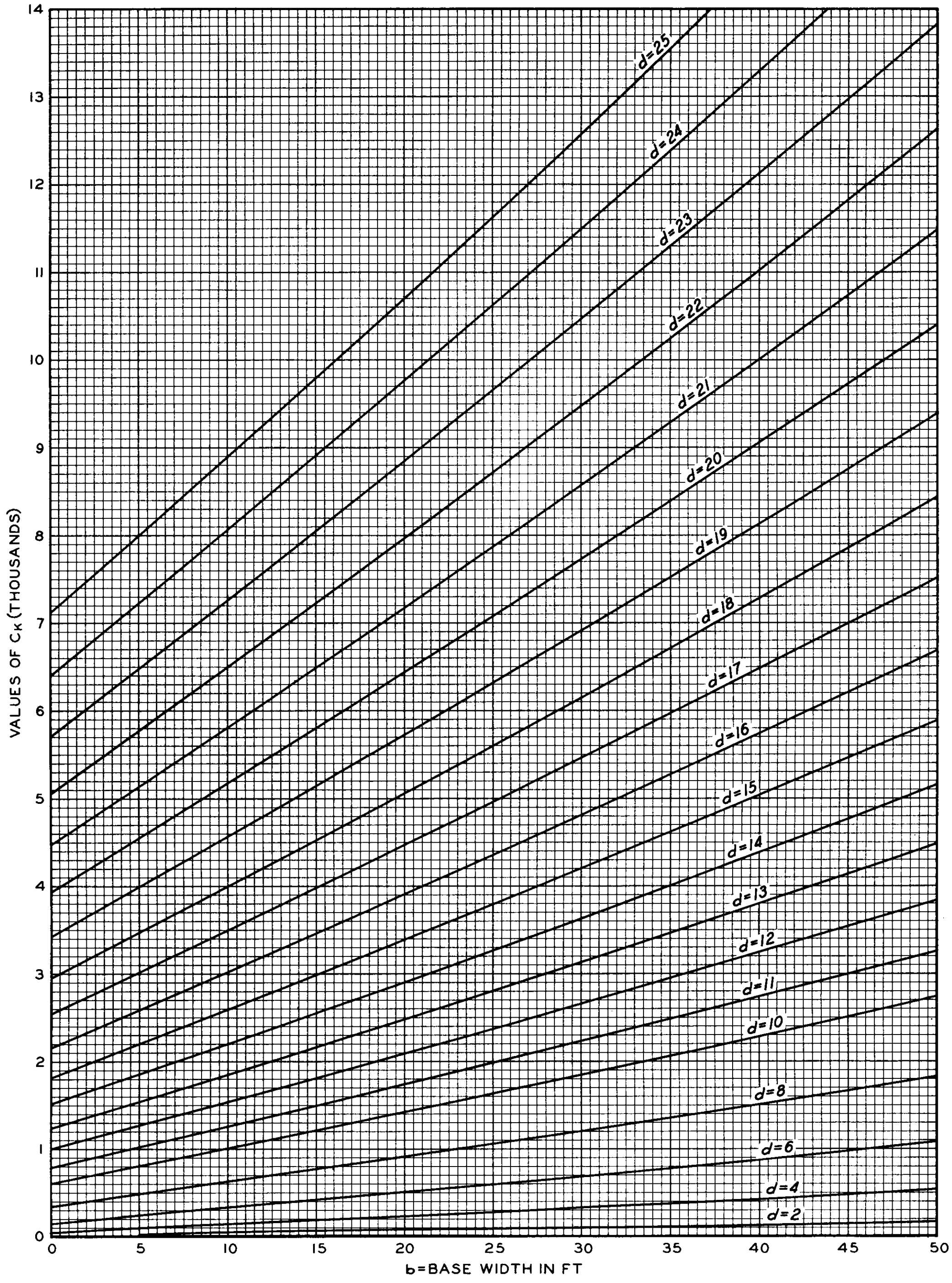
WES 9-54



TRAPEZOIDAL CHANNELS
C_K VS BASE WIDTH
SIDE SLOPE $2\frac{1}{4}$ TO 1

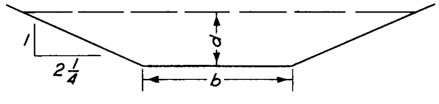
HYDRAULIC DESIGN CHART 610-3/3

WES 9-54



$C_K = AR^{2/3}$

WHERE:
A = AREA
R = HYDRAULIC RADIUS

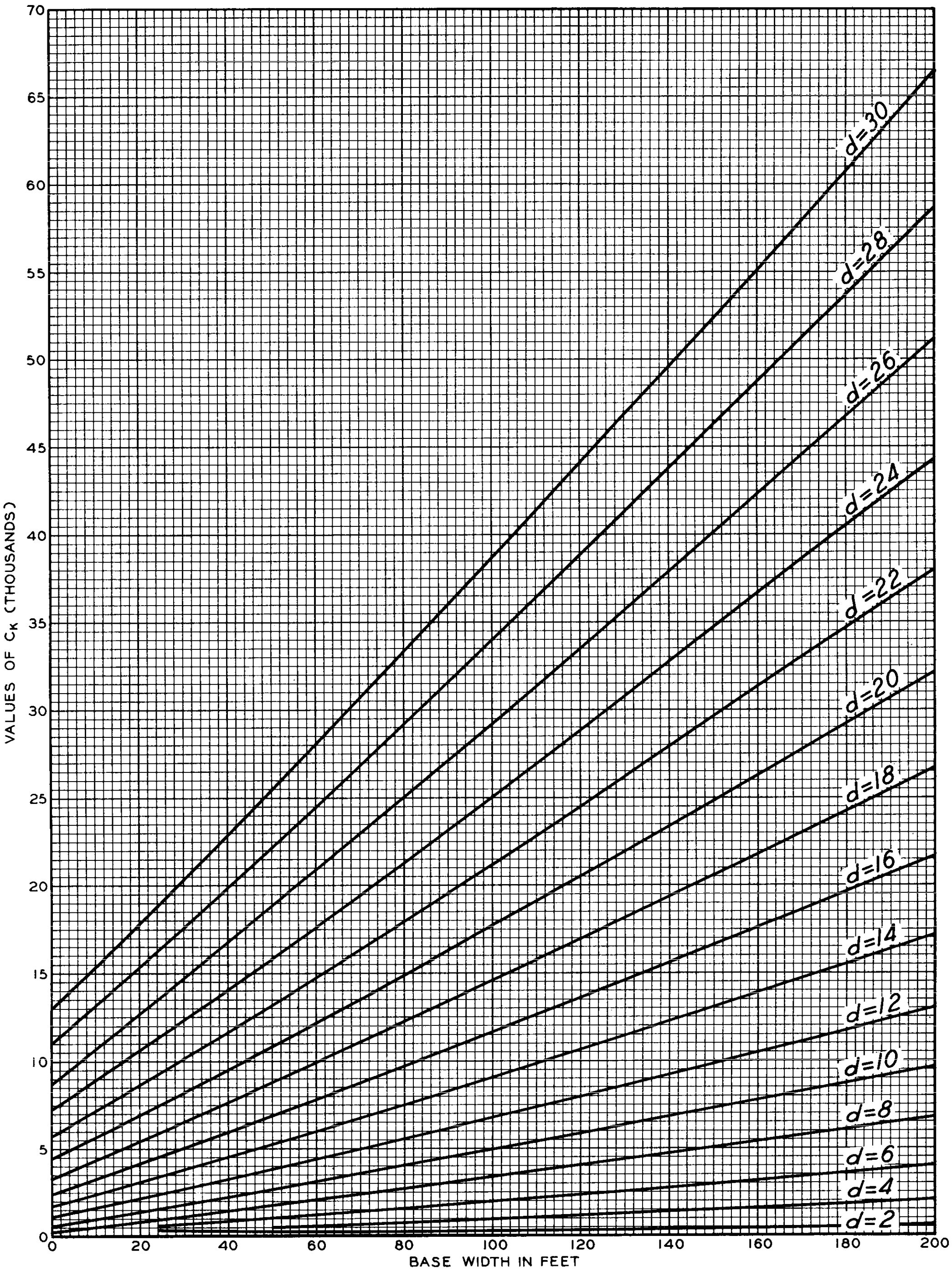


TRAPEZOIDAL CHANNELS
C_K VS BASE WIDTH
SIDE SLOPE $2\frac{1}{4}$ TO 1
BASE WIDTH 0 TO 50 FEET

HYDRAULIC DESIGN CHART 610-3/3-1

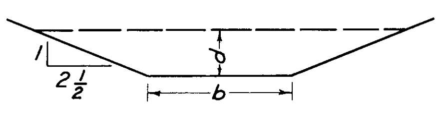
PREPARED BY U. S. ARMY ENGINEER WATERWAYS EXPERIMENT STATION, VICKSBURG, MISSISSIPPI

WES 5-59



$C_K = AR^{2/3}$

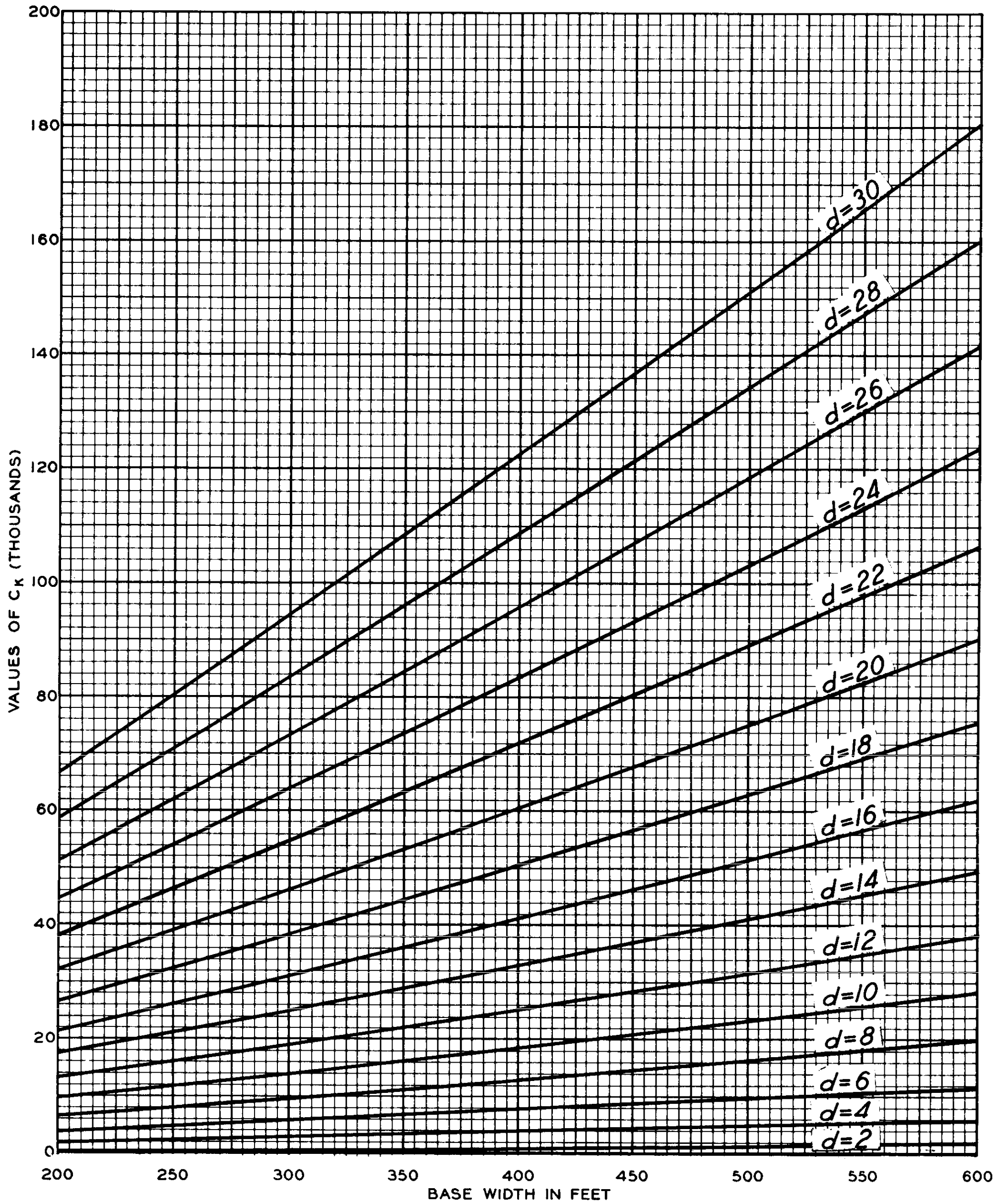
WHERE:
A = AREA
R = HYDRAULIC RADIUS



TRAPEZOIDAL CHANNELS
C_K VS BASE WIDTH
SIDE SLOPE $2\frac{1}{2}$ TO 1

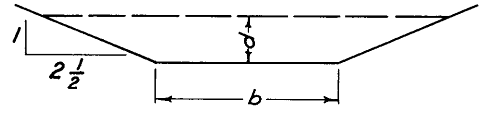
HYDRAULIC DESIGN CHART 610-3/4

WES 9-54



$C_K = AR^{2/3}$

WHERE:
A= AREA
R= HYDRAULIC RADIUS

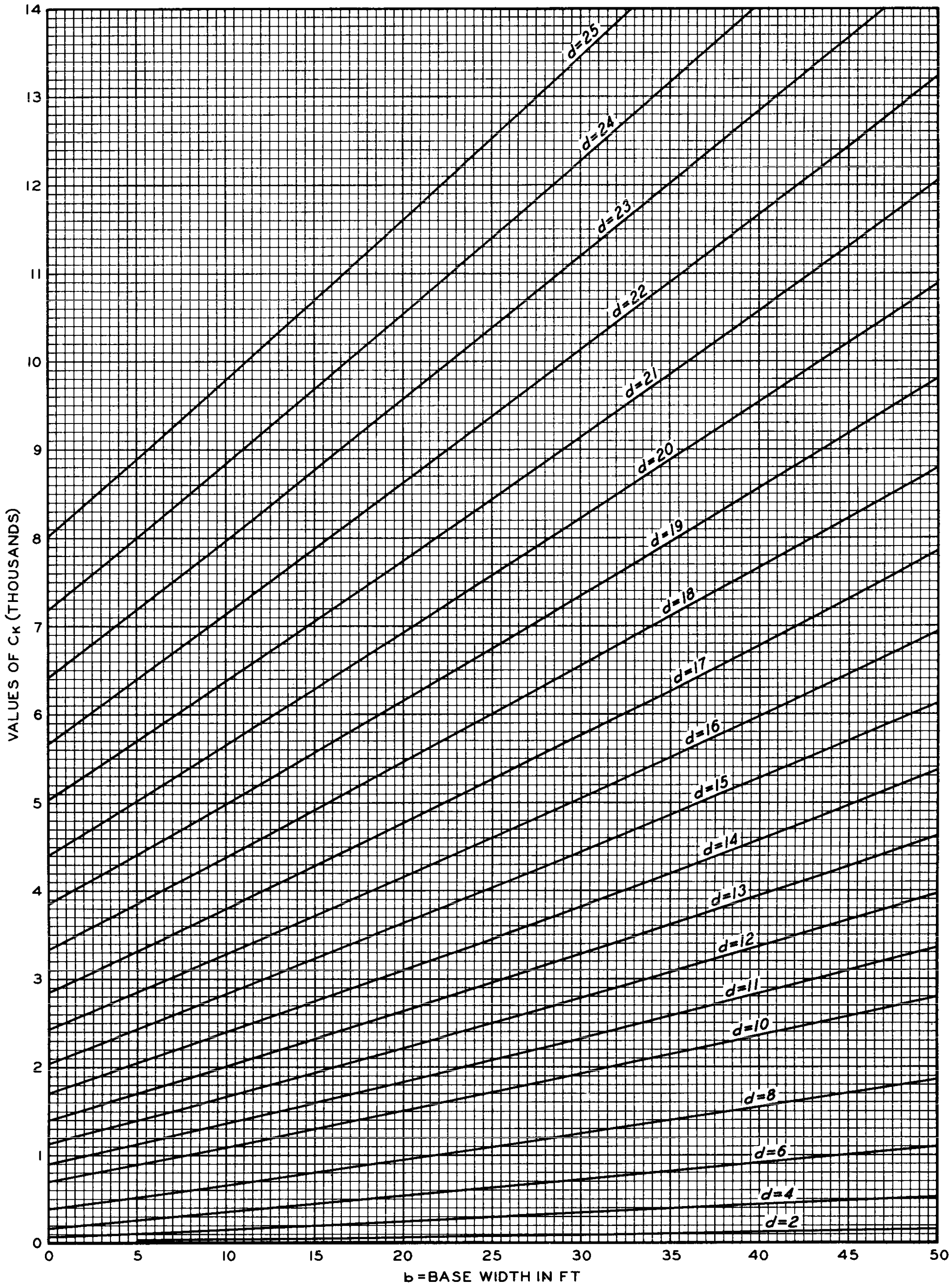


TRAPEZOIDAL CHANNELS
C_K VS BASE WIDTH

SIDE SLOPE $2\frac{1}{2}$ TO 1

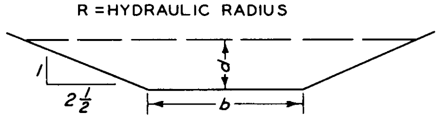
HYDRAULIC DESIGN CHART 610-3/5

WES 9-54



$C_K = AR^{2/3}$

WHERE:
A = AREA
R = HYDRAULIC RADIUS



TRAPEZOIDAL CHANNELS
C_K VS BASE WIDTH
SIDE SLOPE $2\frac{1}{2}$ TO 1
BASE WIDTH 0 TO 50 FEET

HYDRAULIC DESIGN CHART 610-3/5-1

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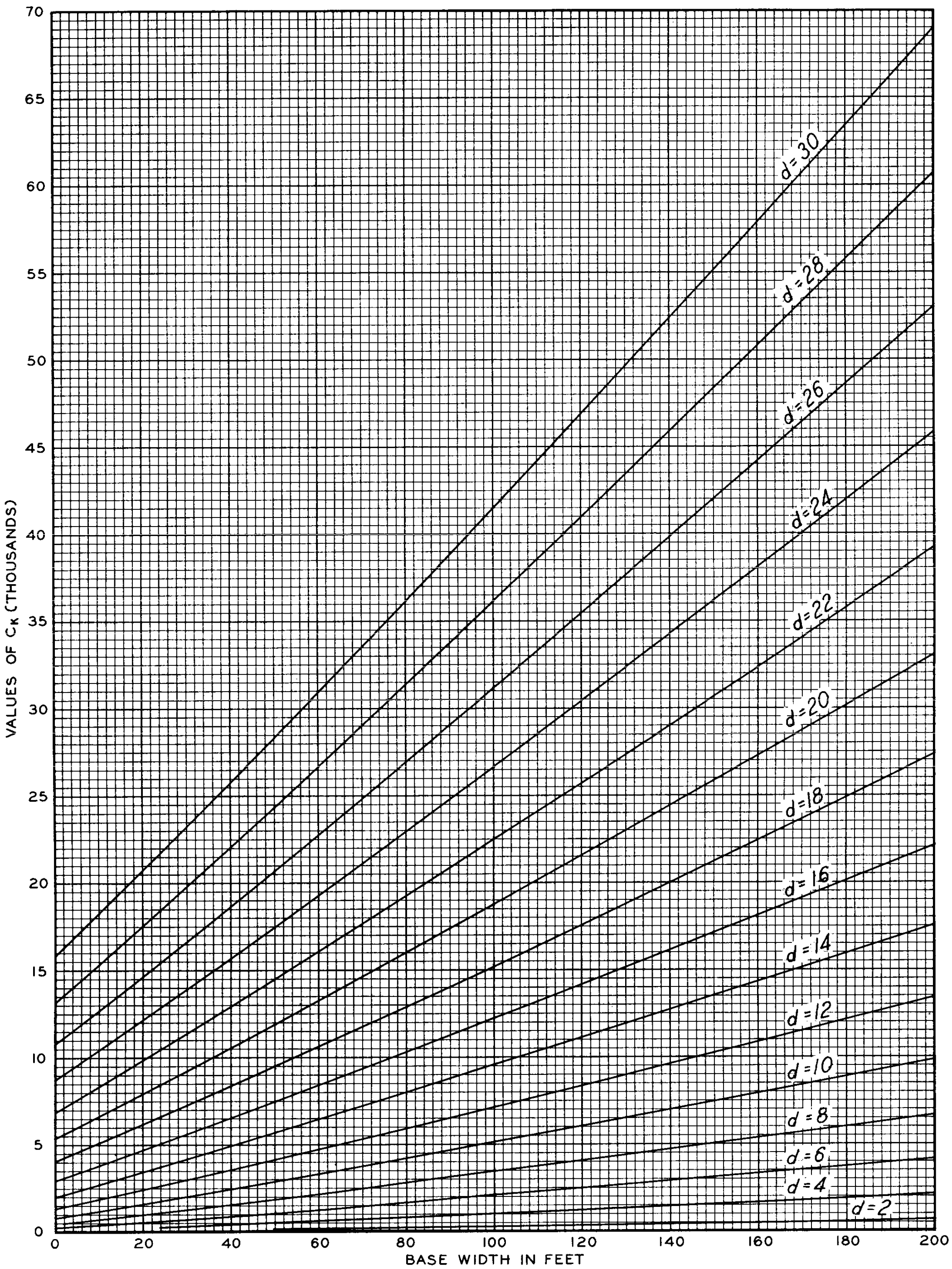
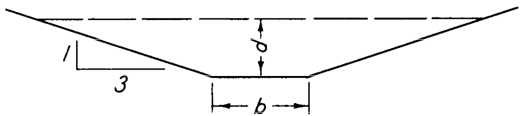


$C_K = AR^{2/3}$

WHERE:

A = AREA

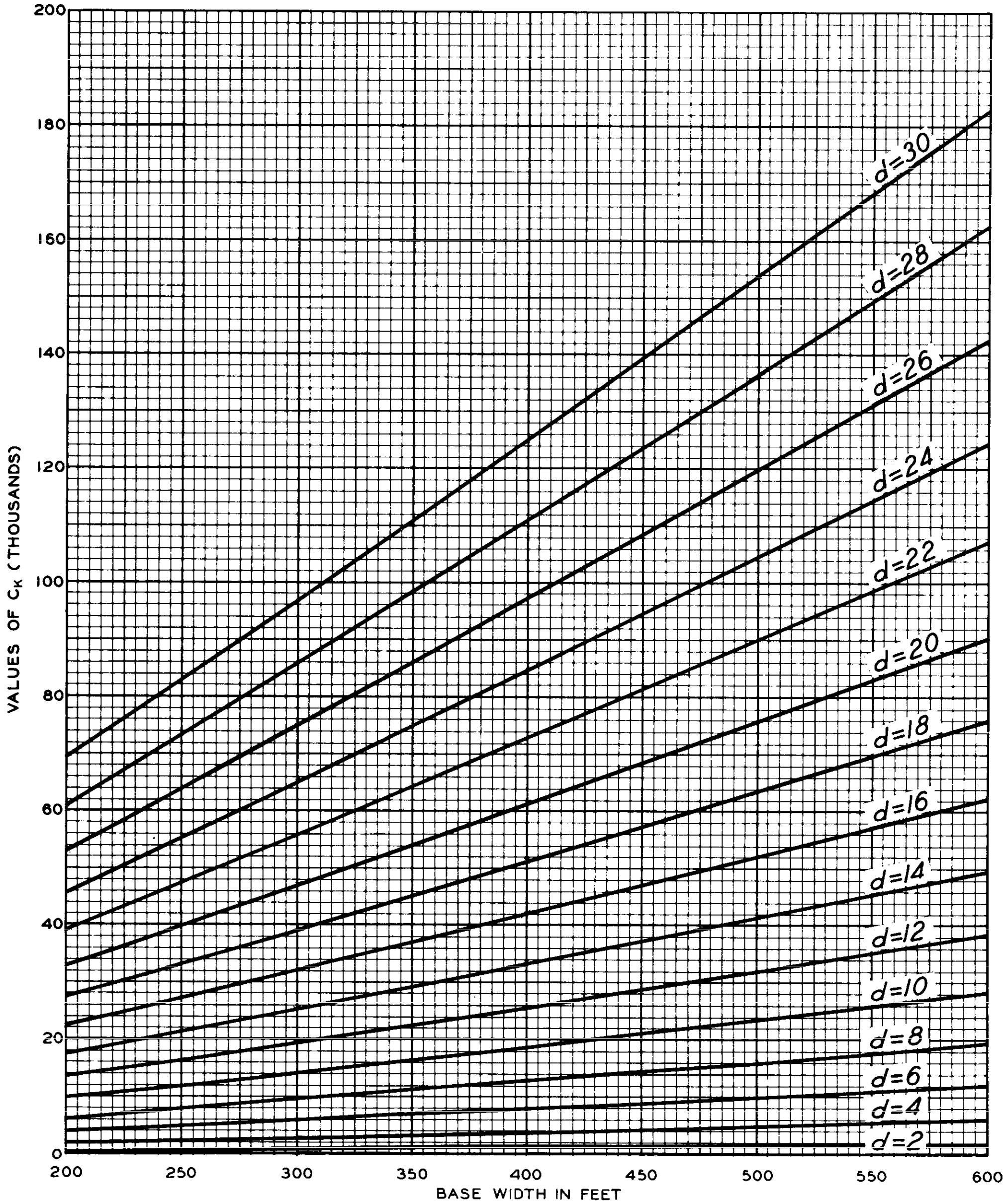
R = HYDRAULIC RADIUS



TRAPEZOIDAL CHANNELS
C_K VS BASE WIDTH
SIDE SLOPE 3 TO 1

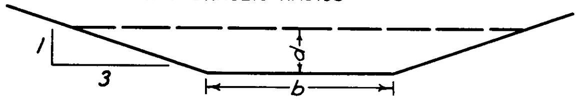
HYDRAULIC DESIGN CHART 610-4

WES 2-54



$C_K = AR^{2/3}$

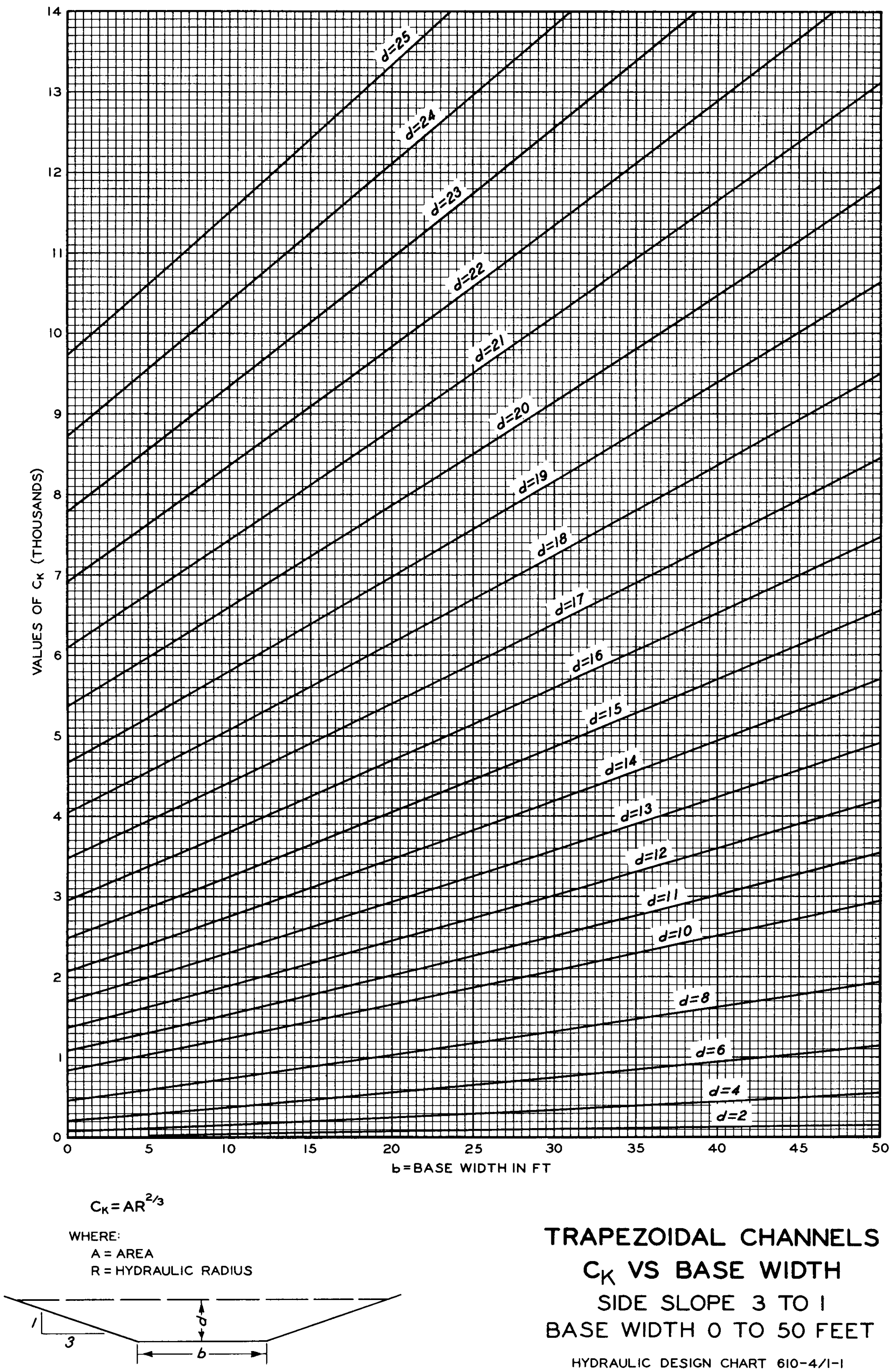
WHERE:
A=AREA
R=HYDRAULIC RADIUS



TRAPEZOIDAL CHANNELS
C_K VS BASE WIDTH
SIDE SLOPE 3 TO 1

HYDRAULIC DESIGN CHART 610-4/1

WES 9-54



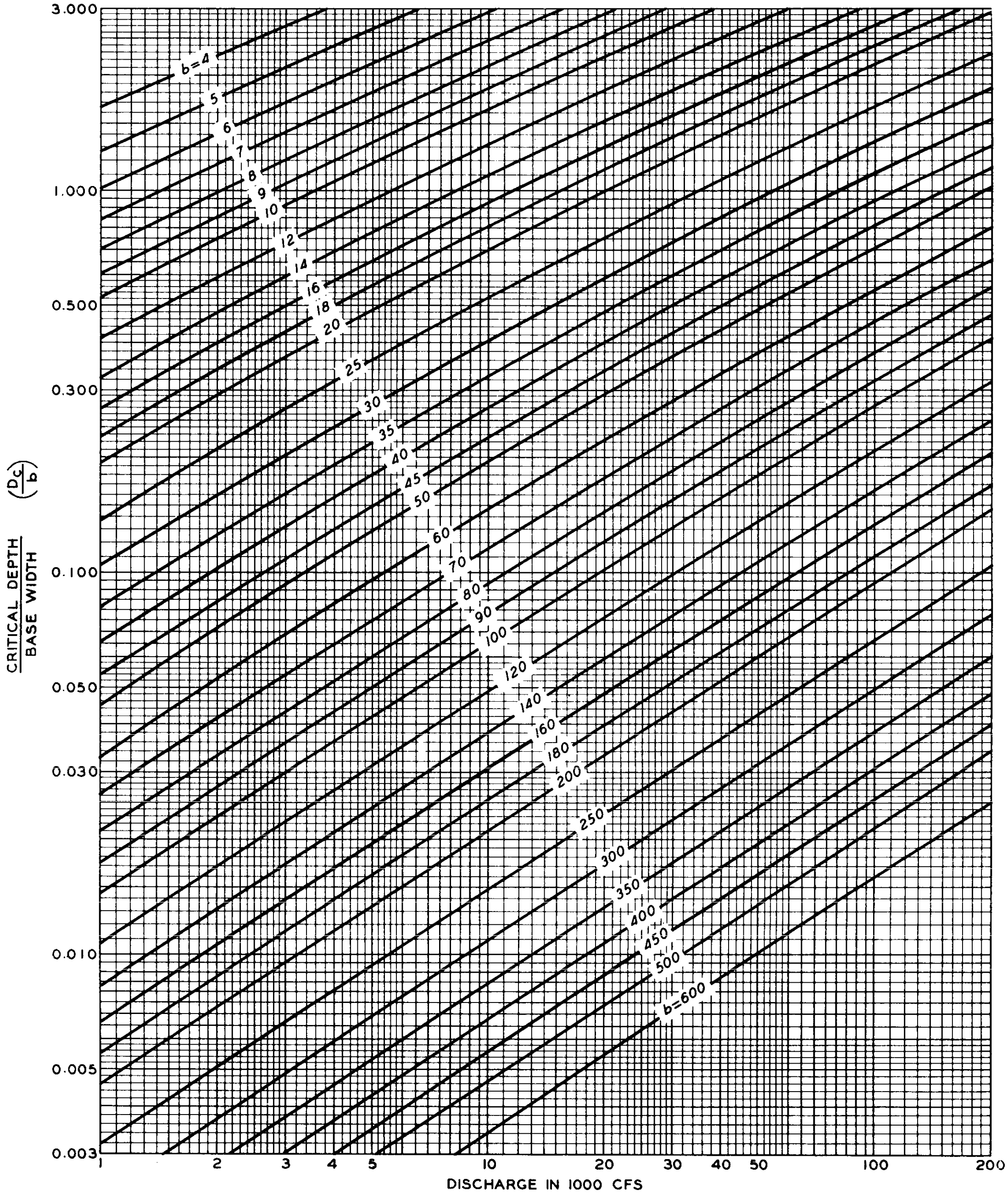
$C_K = AR^{2/3}$

WHERE:
A = AREA
R = HYDRAULIC RADIUS

TRAPEZOIDAL CHANNELS
C_K VS BASE WIDTH
SIDE SLOPE 3 TO 1
BASE WIDTH 0 TO 50 FEET

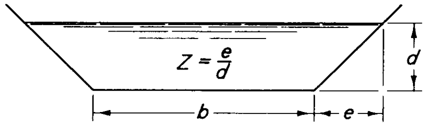
HYDRAULIC DESIGN CHART 610-4/1-1

PREPARED BY U. S. ARMY ENGINEER WATERWAYS EXPERIMENT STATION, VICKSBURG, MISSISSIPPI



BASIC FORMULA:

$$Q = D_c^{3/2}\sqrt{\frac{(b + ZD_c)^3}{b + 2ZD_c} \times g}$$

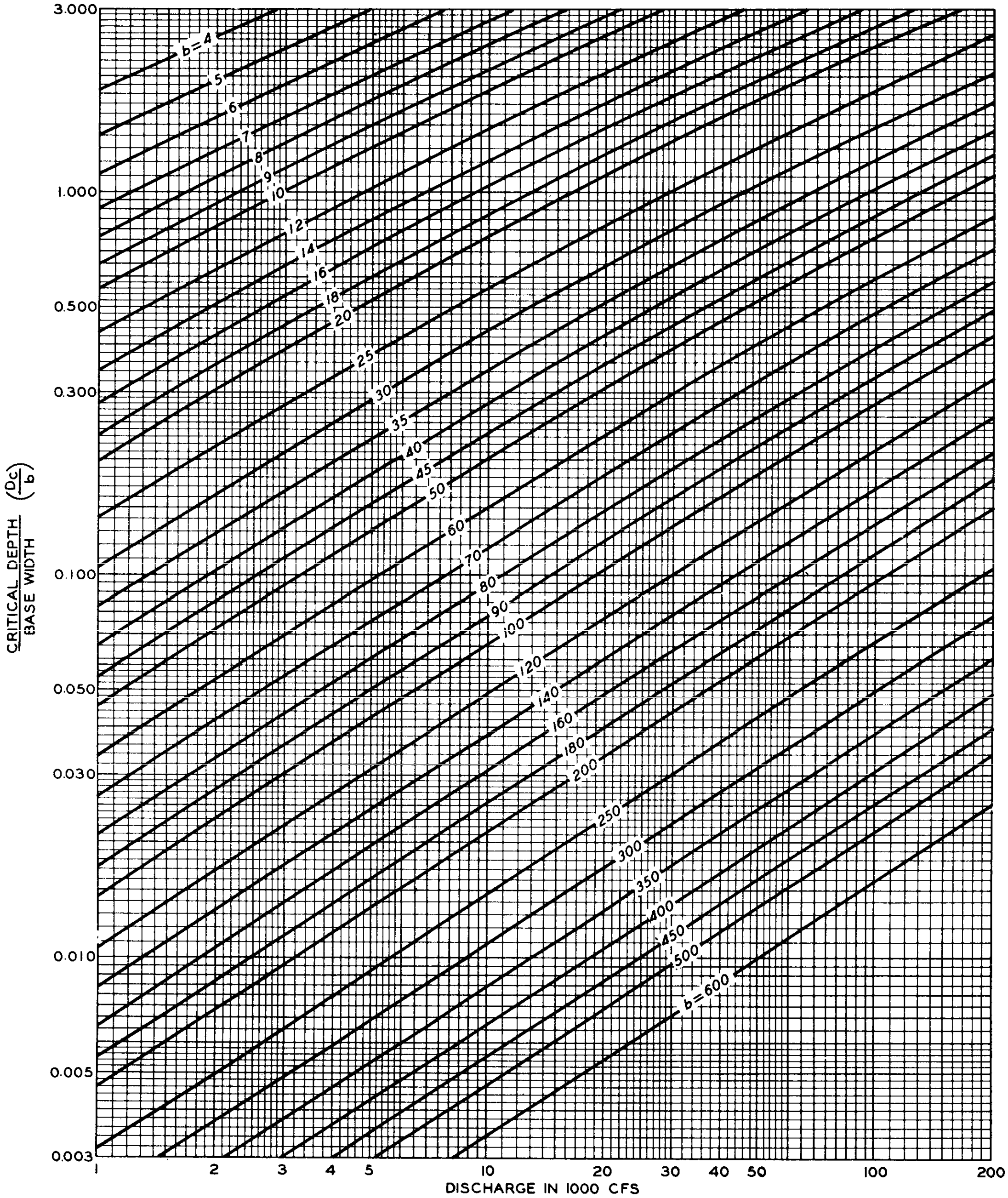


TRAPEZOIDAL CHANNELS CRITICAL DEPTH CURVES

SIDE SLOPE $1\frac{1}{2}$ TO 1

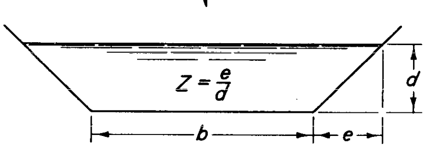
HYDRAULIC DESIGN CHART 610-5/1

WES 9-54



BASIC FORMULA:

$$Q = D_c^{3/2}\sqrt{\frac{(b + ZD_c)^3}{b + 2ZD_c} \times g}$$

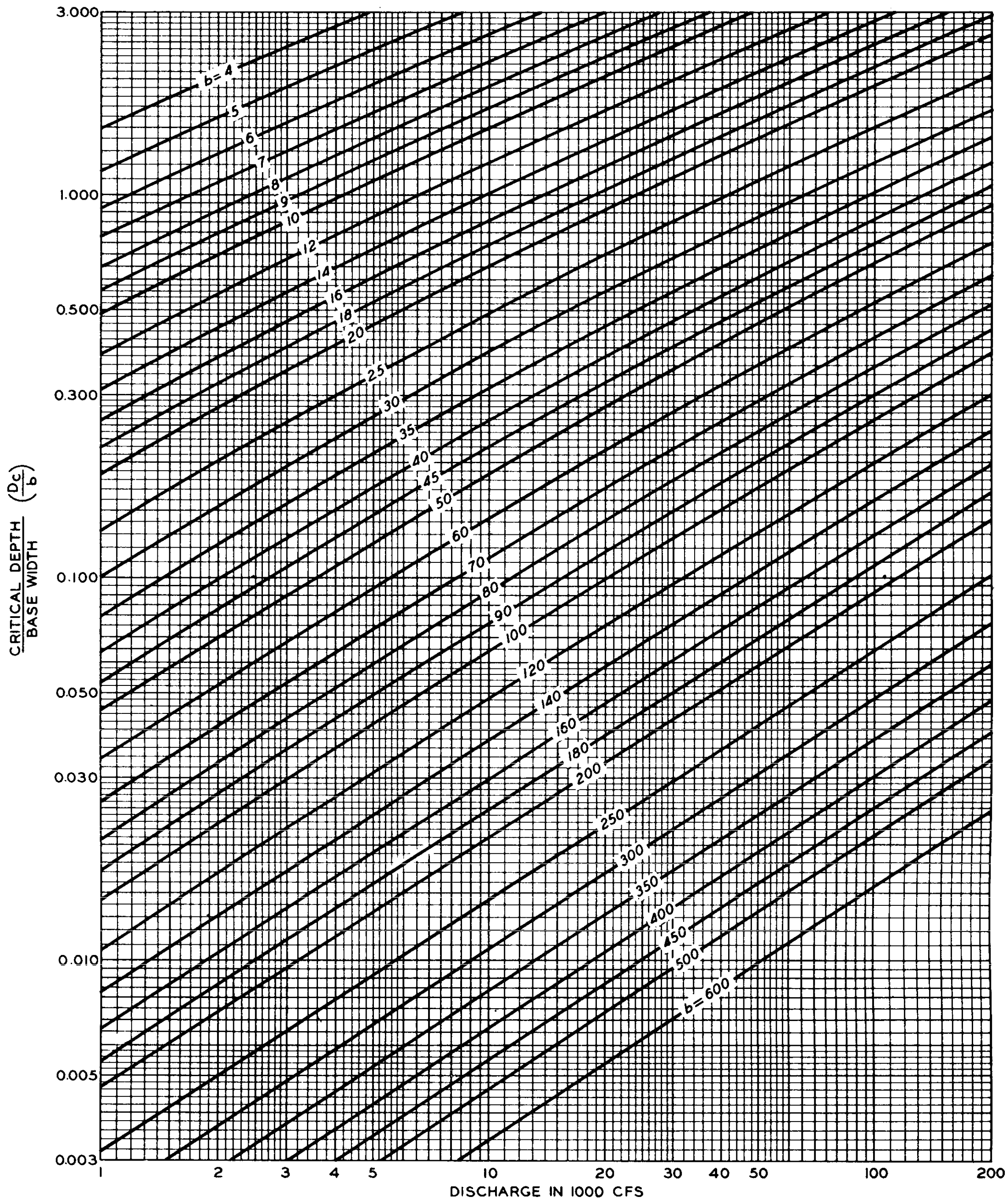


TRAPEZOIDAL CHANNELS CRITICAL DEPTH CURVES

SIDE SLOPE 1 TO 1

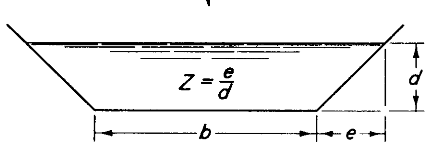
HYDRAULIC DESIGN CHART 610-5

WES 2-54



BASIC FORMULA:

$$Q = D_c^{3/2}\sqrt{\frac{(b + ZD_c)^3}{b + 2ZD_c} \times g}$$

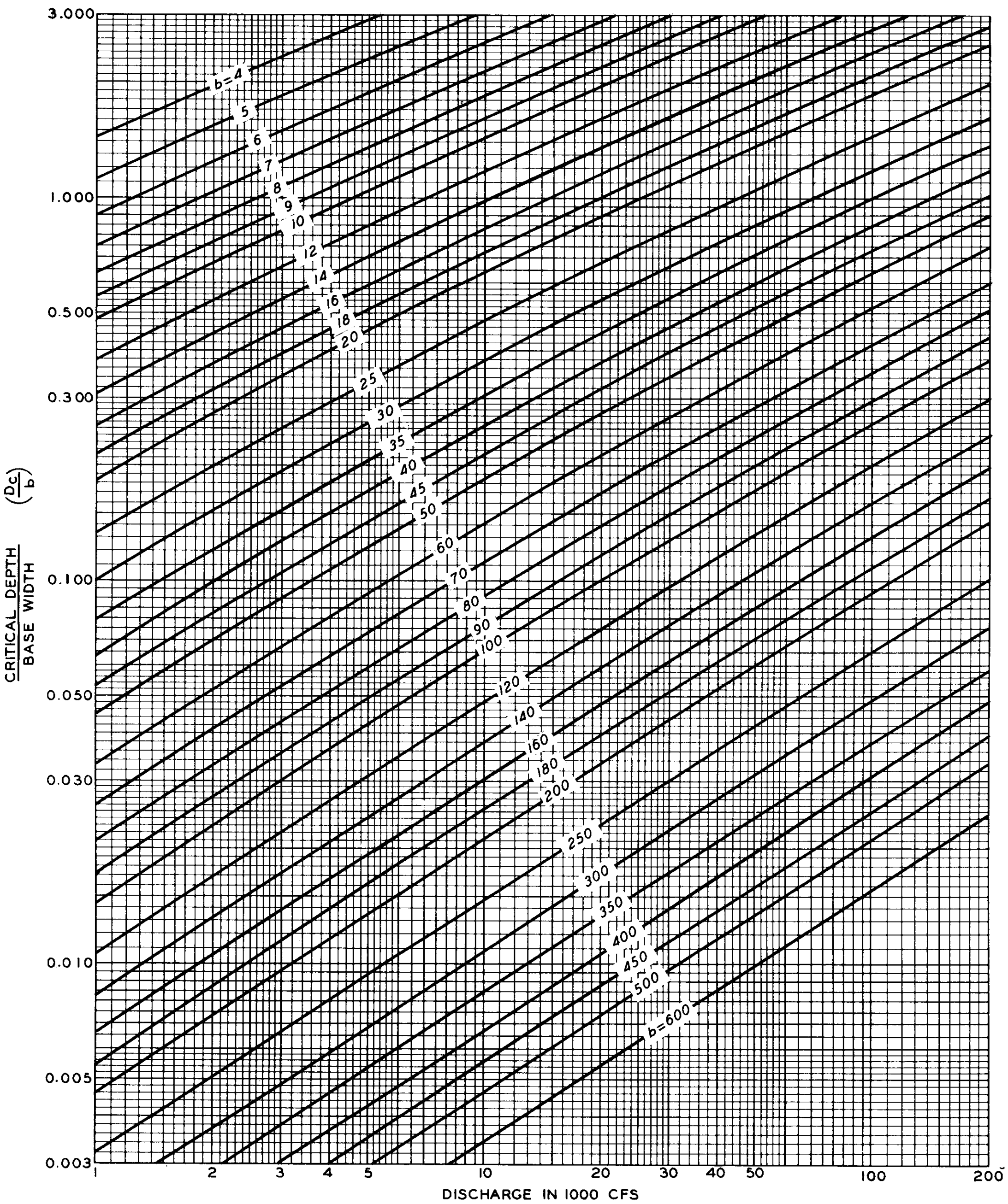


TRAPEZOIDAL CHANNELS
CRITICAL DEPTH CURVES

SIDE SLOPE 2 TO 1

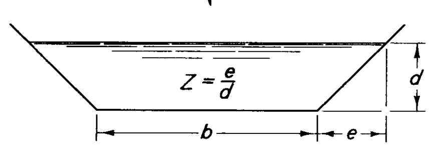
HYDRAULIC DESIGN CHART 610-6

WES 2-54



BASIC FORMULA:

$$Q = D_c^{3/2}\sqrt{\frac{(b+ZD_c)^3}{b+2ZD_c} \times g}$$

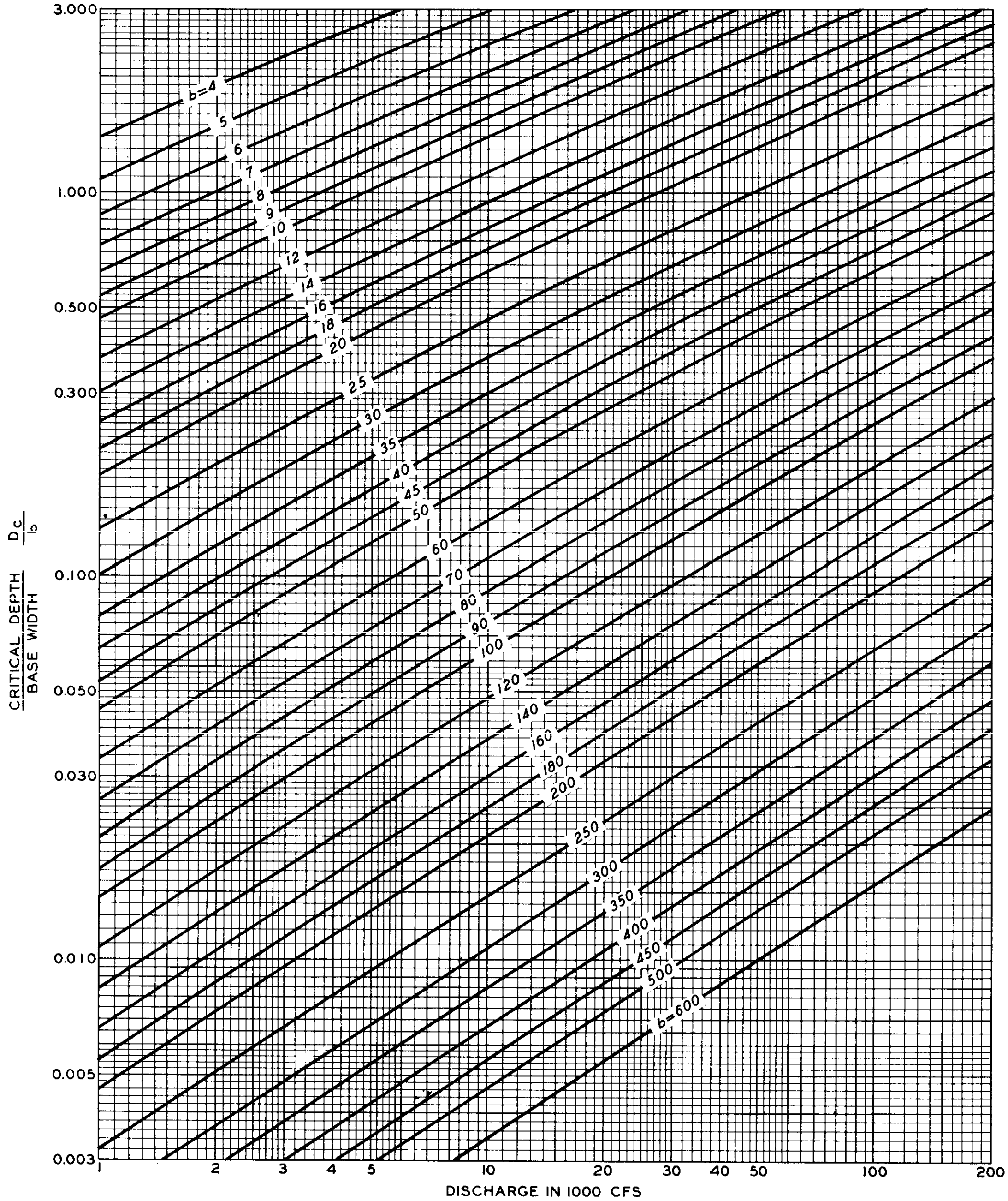


TRAPEZOIDAL CHANNELS CRITICAL DEPTH CURVES

SIDE SLOPE $2\frac{1}{4}$ TO 1

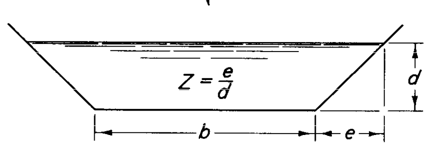
HYDRAULIC DESIGN CHART 610-6/1

WES 9-54



BASIC FORMULA:

$$Q = D_c^{3/2}\sqrt{\frac{(b + ZD_c)^3}{b + 2ZD_c} \times g}$$

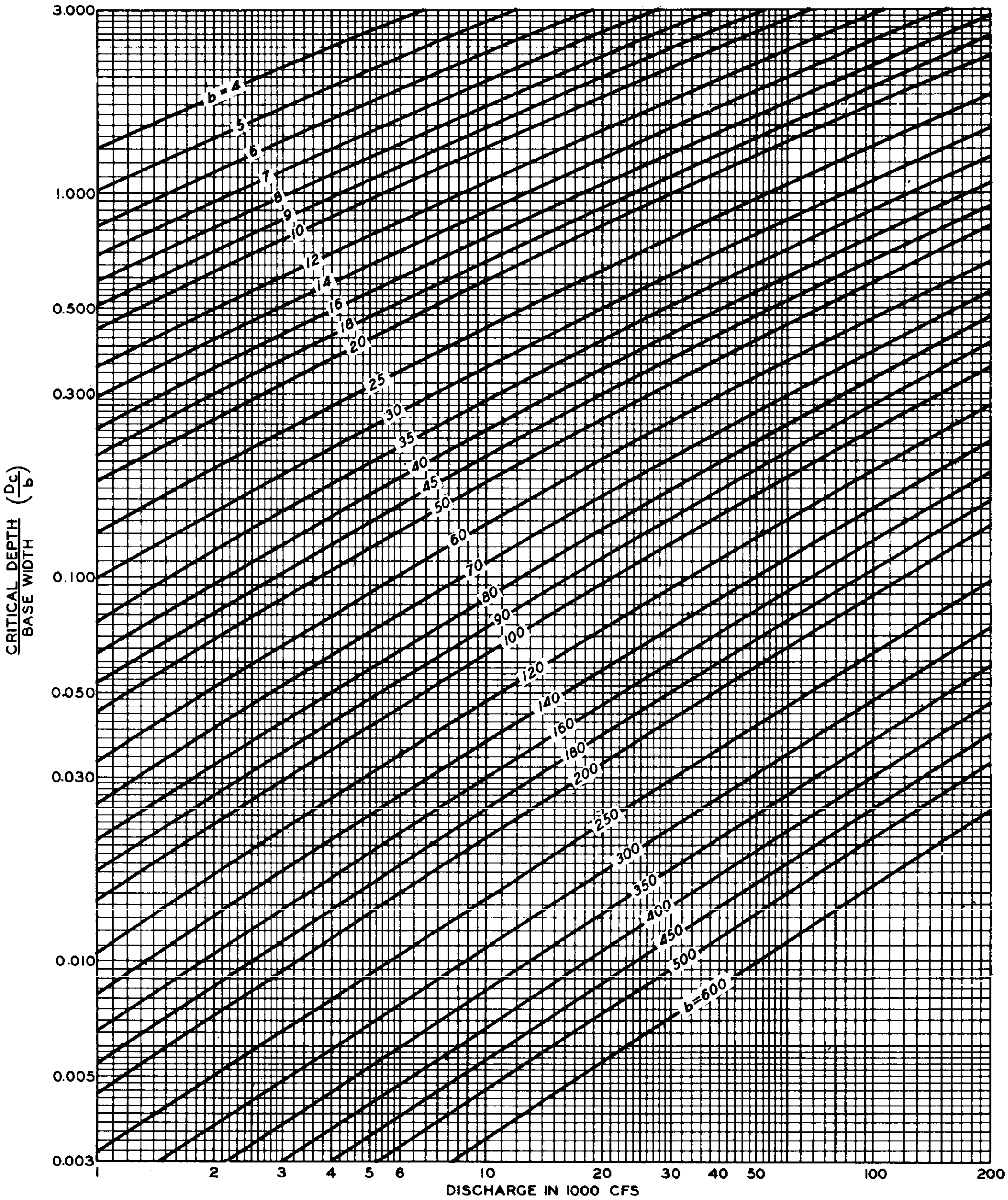


TRAPEZOIDAL CHANNELS CRITICAL DEPTH CURVES

SIDE SLOPE $2\frac{1}{2}$ TO 1

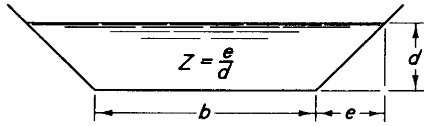
HYDRAULIC DESIGN CHART 610-6/2

WES 9-54



BASIC FORMULA:

$$Q = D_c^{3/2}\sqrt{\frac{(b + ZD_c)^3}{b + 2ZD_c} \times g}$$



TRAPEZOIDAL CHANNELS
CRITICAL DEPTH CURVES

SIDE SLOPE 3 TO 1

HYDRAULIC DESIGN CHART 610-7

WES 2-54

HYDRAULIC DESIGN CRITERIA

SHEETS 610-8 TO 610-9/1-1

OPEN CHANNEL FLOW

RECTANGULAR SECTIONS

1. Hydraulic Design Charts 610-8 to 610-9/1-1 are aids for reducing the computation effort in the design of rectangular channels. These charts are useful also in the backwater computations presented on Chart 010-2.

2. Basic Equations. Chart 610-8 shows plots of normal depth (y_o) with respect to discharge per foot of width (q) for wide rectangular sections where the side wall effect may be neglected. Normal depth curves are shown for Manning's n of 0.011 and 0.013 and for slopes of 0.01 to 0.50. The roughness and slopes values are those commonly used in the design of spillway chutes. The curves are computed from a variation of the Manning formula for open channel flow.

$$q = cy_o^{5/3}$$

where

$$c = \frac{1.486\ S^{1/2}}{n}$$

Critical depth (y_c) with respect to q is also plotted on this chart. Critical depth in rectangular channels is a function of unit discharge only

$$y_c = \sqrt[3]{\frac{q^2}{g}}$$

3. Charts 610-9 through 610-9/1-1 in conjunction with Charts 610-1 and -1/1 can be used to determine normal depths (y_o) for any rectangular channel. These charts are similar to Charts 610-2 to 610-4/1-1 and were developed in the manner described in paragraph 2 of Sheets 610-1 to 610-7.

4. Application. Preliminary design of rectangular channels for uniform subcritical or supercritical flows is readily determined by use of the charts in the following manner:

 a. Two-dimensional flow. For wide channels, y_o and y_c can be obtained directly from Chart 610-8 for given values of n , S , and q .

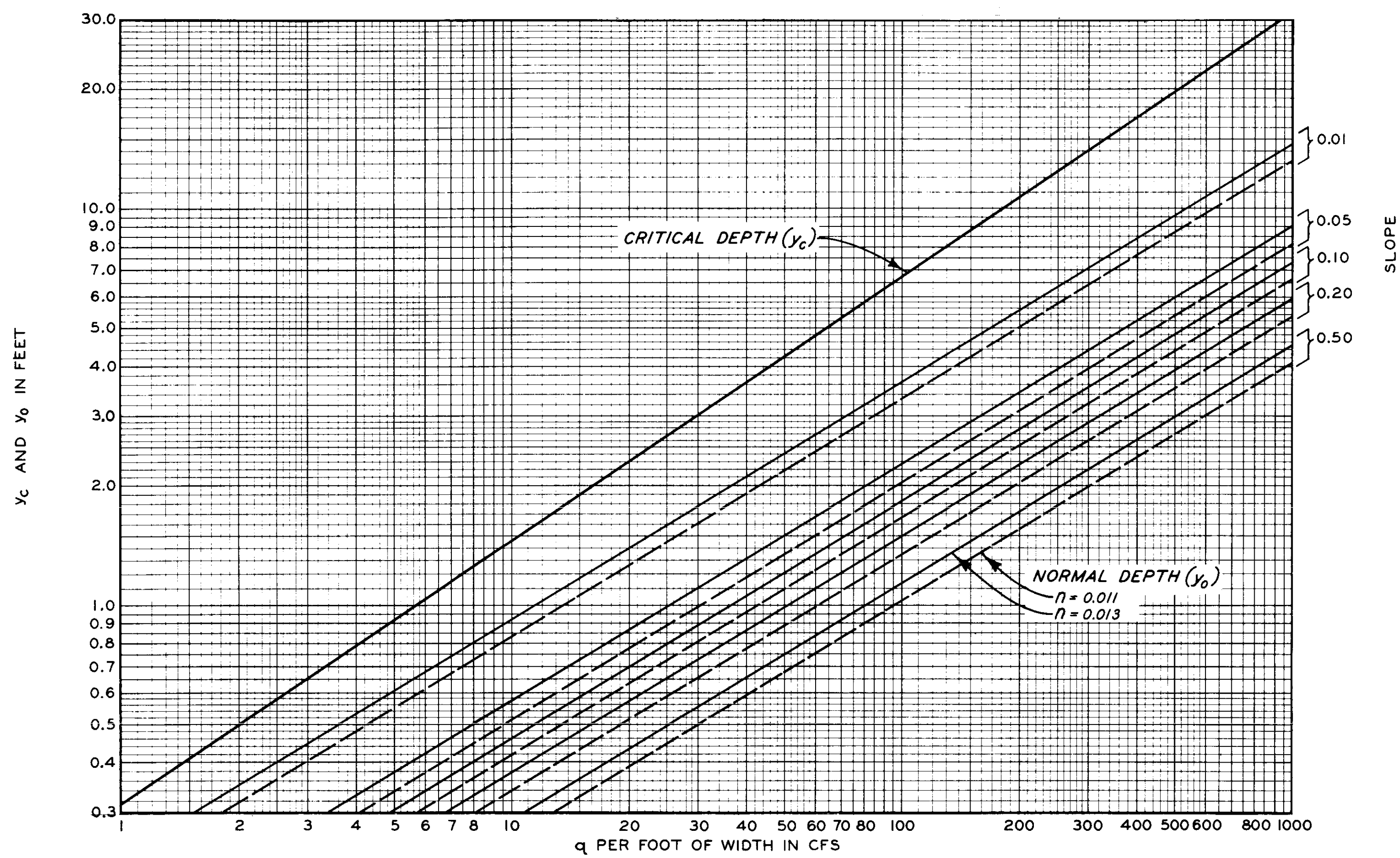
b. Three-dimensional flow. For all channels, Charts 610-9 through 610-9/1-1 can be used in the manner described in paragraphs 3a, b, and c, Sheets 610-1 to 610-7. Critical depth can be obtained from Chart 610-8.

c. Normal depth for three-dimensional flow can also be computed from Chart 610-8 by use of the following table:

b/d_2	d_3/d_2
2	1.38
5	1.17
10	1.07
15	1.05
25	1.03

where

b = channel width in ft
d_2 = two-dimensional flow depth in ft
d_3 = three-dimensional flow depth in ft.



BASIC EQUATIONS

$$q = Cy_0^{5/3}; \quad y_c = \sqrt[3]{\frac{q^2}{g}}$$

WHERE: q = DISCHARGE PER FOOT OF WIDTH

$C = \frac{1.486\, S^{1/2}}{n}$

y_0 = NORMAL DEPTH IN FEET

y_c = CRITICAL DEPTH IN FEET

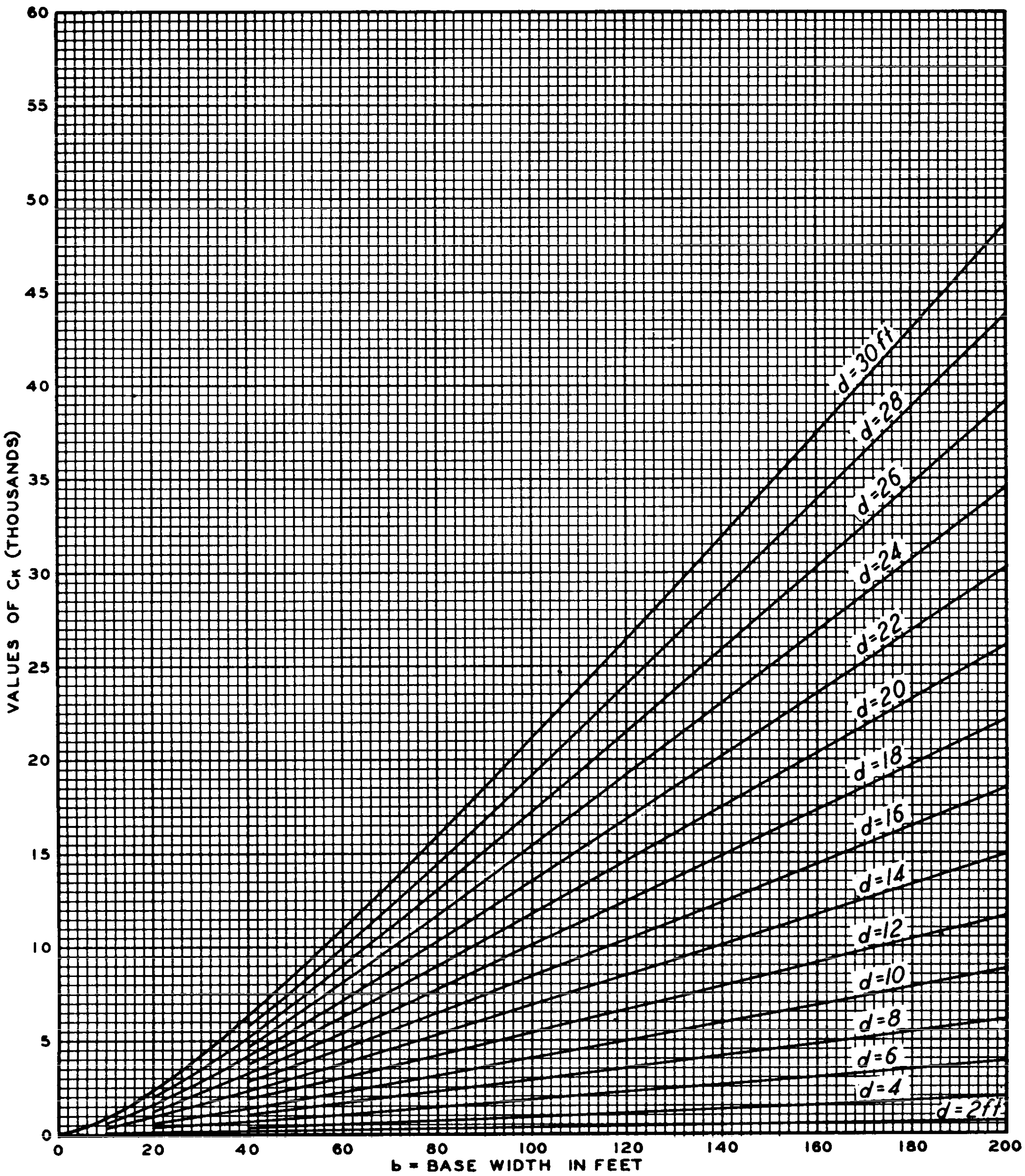
g = GRAVITY

OPEN CHANNEL FLOW

NORMAL AND CRITICAL DEPTHS WIDE RECTANGULAR SECTIONS

HYDRAULIC DESIGN CHART 610-8

WES 3-56



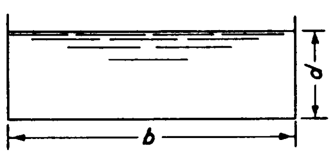
BASIC EQUATION

$C_K = AR^{2/3}$

WHERE:

A = AREA

R = HYDRAULIC RADIUS



OPEN CHANNEL FLOW

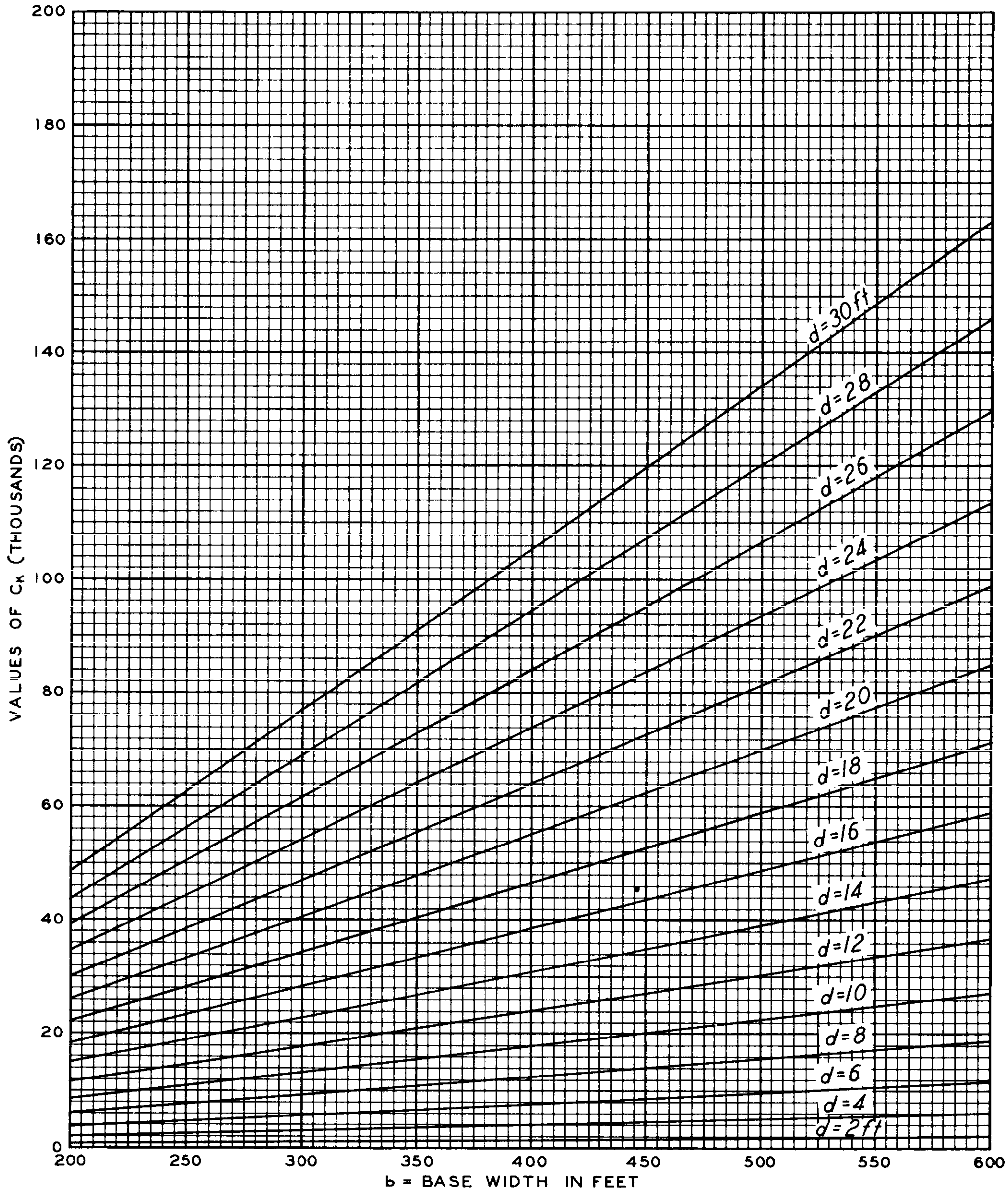
C_K VS BASE WIDTH

RECTANGULAR SECTIONS

BASE WIDTHS OF 0 TO 200 FT

HYDRAULIC DESIGN CHART 610-9

WES 3-56



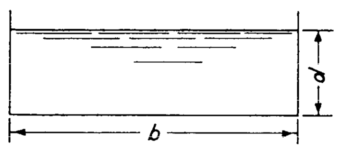
BASIC EQUATION

$C_K = AR^{2/3}$

WHERE:

A = AREA

R = HYDRAULIC RADIUS



OPEN CHANNEL FLOW

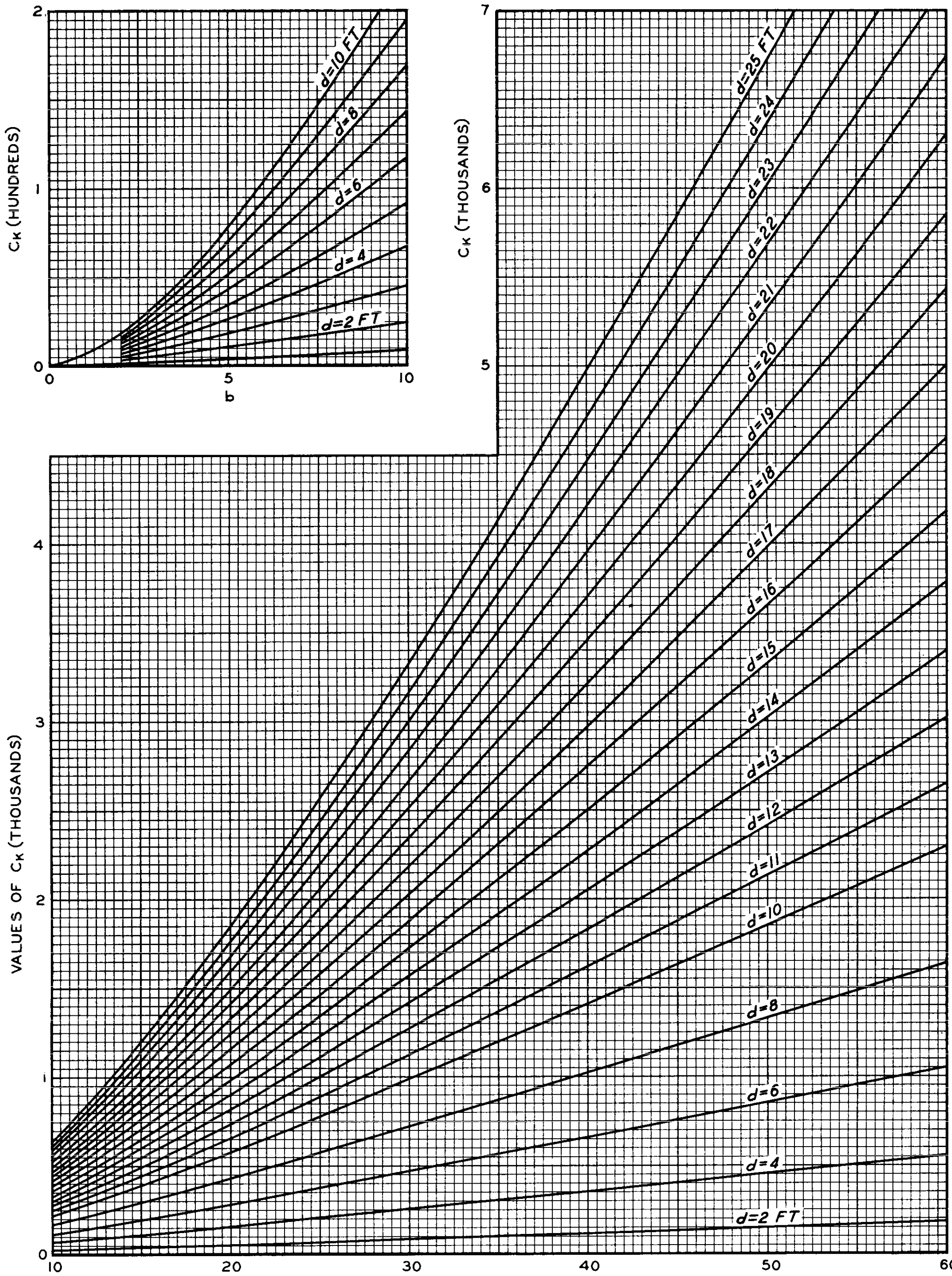
C_K VS BASE WIDTH

RECTANGULAR SECTIONS

BASE WIDTHS OF 200 TO 600 FT

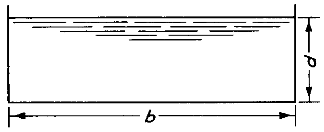
HYDRAULIC DESIGN CHART 610-9/1

WES 3-56



$C_K = AR^{2/3}$

WHERE:
A=AREA
R=HYDRAULIC RADIUS



OPEN CHANNEL FLOW

C_K VS BASE WIDTH RECTANGULAR SECTIONS BASE WIDTH 0 TO 60 FEET

HYDRAULIC DESIGN CHART 610-9/1-1

HYDRAULIC DESIGN CRITERIA

SHEETS 623 TO 624-1

SUBCRITICAL OPEN CHANNEL FLOW

DROP STRUCTURES

1. Purpose. A channel invert slope can vary from a maximum defined by a line connecting the crests of two drop structures to a minimum fixed by the elevation of the end sill of the upstream structure, the elevation of the crest of the downstream structure, and the distance between the two structures. The minimum slope should be that which results in stable channel conditions.

2. Hydraulic Design Charts (HDC's) 623 to 624-1 present design criteria for drop structures in subcritical flow used to prevent channel degradation. The criteria shown in HDC 623 are recommended for drops where the unit discharge is large relative to the drop height. The design criteria shown in HDC 624 and 624/1 are recommended for drop structures where both the unit discharge and drop height are large and where optimum energy dissipation is required to reduce downstream erosion. In most cases economy of construction is the deciding factor.

3. Background. The accepted relation between the height of drop h (difference in elevation between the crest and the end sill of the drop structure), critical depth d_c at the drop, and the required stilling basin length L_B is attributed to Etcheverry[1] and defined by the equation

$$L_B = C_L \sqrt{hd_c} \tag{1}$$

where C_L is an empirical apron length coefficient. Studies by Morris and Johnson[2] resulted in design of the CIT (California Institute of Technology) structure restricted to h/d_c ratios greater than 1.0. Subsequent studies by Vanoni and Pollak[3] included ratios as low as 0.3. While initial research efforts were directed toward erosion control in gullies, subsequent application has been mostly in alluvial streams.

4. Donnelly and Blaisdell[4] investigated drop structures having h/d_c ratios from 1 to 15 and developed the SAF drop structure for primary use in the control of erosion in gullies. The major difference in CIT and SAF structures is the difference in tailwater depths, i.e. shallow and deep, respectively.

5. CIT-Type Drop Structures. Extensive WES tests[5] on the CIT-type structure resulted in the design criteria given in HDC 623. The Vanoni and Pollak results appear to correlate well with the WES tests. WES tests showed that optimum structure performance is obtained if the

structure is designed to have a tailwater-critical depth ratio between 1.25 and 1.67. This results in a strong ground roller, a confined, strong and stable surface roller, and a depressed secondary roller downstream. Curved, upstream abutment walls are recommended for narrow channels to help prevent concentration of the flow. For wide channels with flow width ≥ 20 times the depth, rectangular abutments are satisfactory. Stilling basin training walls should be sufficiently high to prevent the tailwater returning over the walls into the stilling basin. Wing walls at the end of the basin are not recommended. The channel edge should be recessed as indicated in HDC 623.

6. SAF-Type Drop Structures. The SAF-type drop structure[4,6] (HDC's 624 and 624-1) is recommended for designs having large unit discharges and drop heights. The basic layout is shown in HDC 624. The primary controlling parameter in this design is the location at which the upper nappe of the falling jet impinges on the stilling basin floor. This is a function of the total fall of the jet and the depth of the tailwater. Dimensionless curves for determining the impact location of the upper nappe on the basin floor are shown in HDC 624-1.

7. The dimensions of the stilling basin are computed from the following equations.

$$L_B = X_a + X_b + X_c \tag{2}$$

where L_B equals basin length. HDC 624 graphically defines the distance X_a , X_b , and X_c . Numerical values of X_b and X_c are obtained from the following equations:

$$X_b = 0.8d_c \tag{3}$$

$$X_c = 1.75d_c \tag{4}$$

Substituting equations 3 and 4 into equation 1 results in

$$L_B = X_a + 2.55d_c \tag{5}$$

with d_c as defined in paragraph 3 and as shown in HDC's 623 and 624. Laboratory tests[4] have resulted in the following recommendations for baffle pier and end sill heights.

$$\text{Baffle pier height} = 0.8d_c \tag{6}$$

$$\text{End sill height } h' = 0.4d_c \tag{7}$$

These tests also showed that optimum basin performance occurs when the baffle pier width and spacing effect a 50 to 60 percent reduction in flow width and the minimum tailwater depth is not less than $2.15d_c$.

8. Design Discharge. Design discharge for the drop structure should be computed using the equation

$$Q = CLH^{3/2} \tag{8}$$

where

Q = design discharge, cfs
C = discharge coefficient = 3.0*
L = length of the drop structure crest, ft
H = energy head on the crest, ft

The length L of the weir should effect optimum use of channel cross section upstream. A trial-and-error procedure should be used to balance the crest height and width with the channel cross section.

9. Riprap Protection. Riprap protection should be provided immediately upstream and downstream of each structure. It is recommended that design criteria given in HDC 712-1 be used to meet stilling requirements and that given in EM 1110-2-1601 (reference 7) for upstream protection.

10. References.

(1) Etcheverry, B. A., Irrigation Practice and Engineering. 1st ed., Chapter VII, McGraw-Hill Book Company, New York, N. Y., 1916.

(2) Morris, B. T. and Johnson, D. C., "Hydraulic design of drop structures for gully control." Transactions, American Society of Civil Engineers, vol 108 (1943), pp 887-940.

(3) Vanoni, V. A. and Pollak, R. E., Experimental Design of Low Rectangular Drops for Alluvial Flood Channels. Report No. E-82, California Institute of Technology, Pasadena, Calif., September 1959.

(4) Donnelly, C. A. and Blaisdell, F. W., Straight Drop Spillway Stilling Basin. Technical Paper No. 15, Series B, St. Anthony Falls Hydraulic Laboratory, University of Minnesota, Minneapolis, Minn., November 1954.

(5) U. S. Army Engineer Waterways Experiment Station, CE, Drop Structure for Gering Valley Project, Scottsbluff County, Nebraska, Hydraulic Model Investigation, by T. E. Murphy. Technical Report No. 2-760, Vicksburg, Miss., February 1967.

(6) U. S. Department of Agriculture, Soil Conservation Service, Engineer- Handbook, Drop Spillways. Section 11, Type C, Washington, D. C., p 5-11.

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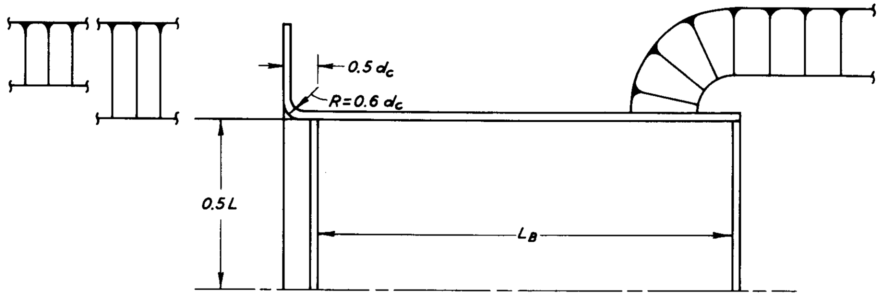
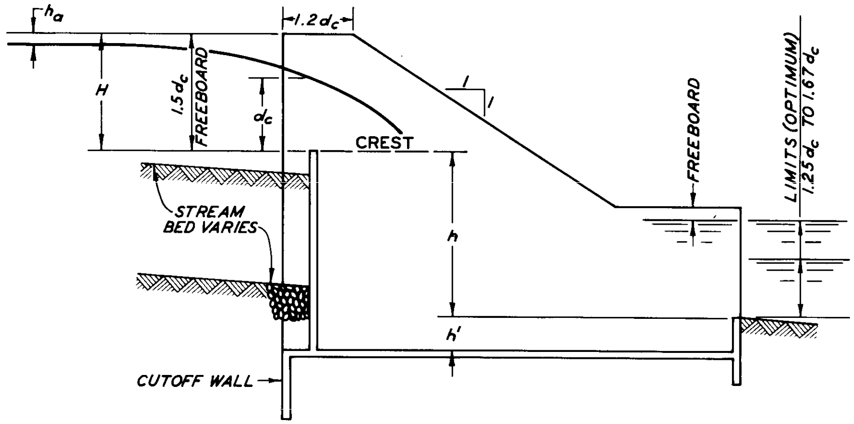
* Reduced for submergence effects when applicable.

(7) U. S. Army, Office, Chief of Engineers, Engineering and Design; Hydraulic Design of Flood Control Channels. Engineer Manual EM 1110-2-1601, Washington, D. C., 1 July 1970.



HALF PLAN

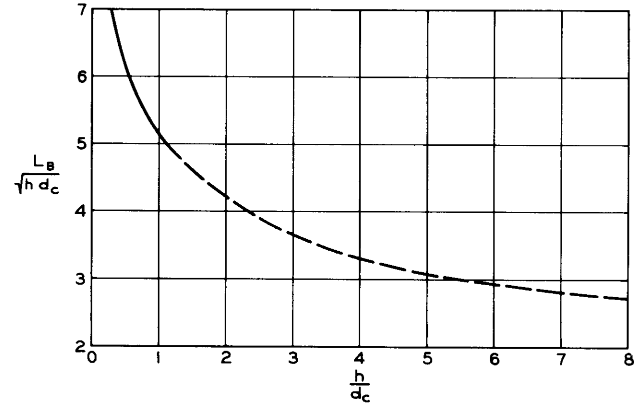


CENTER-LINE SECTION

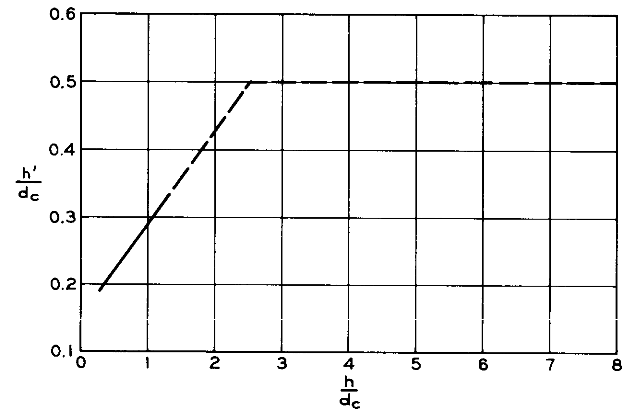
NOTE:

d_c = CRITICAL DEPTH OVER CREST
h = HEIGHT OF DROP
h' = HEIGHT OF END SILL
H = HEAD ON WEIR = $\frac{3}{2}$ (d_c)
h_a = VELOCITY HEAD
L_B = LENGTH OF BASIN
L = LENGTH OF WEIR CREST

EXTRAPOLATED PORTIONS OF THE CURVES ARE NOT RECOMMENDED FOR LARGE STRUCTURES.



LENGTH OF BASIN



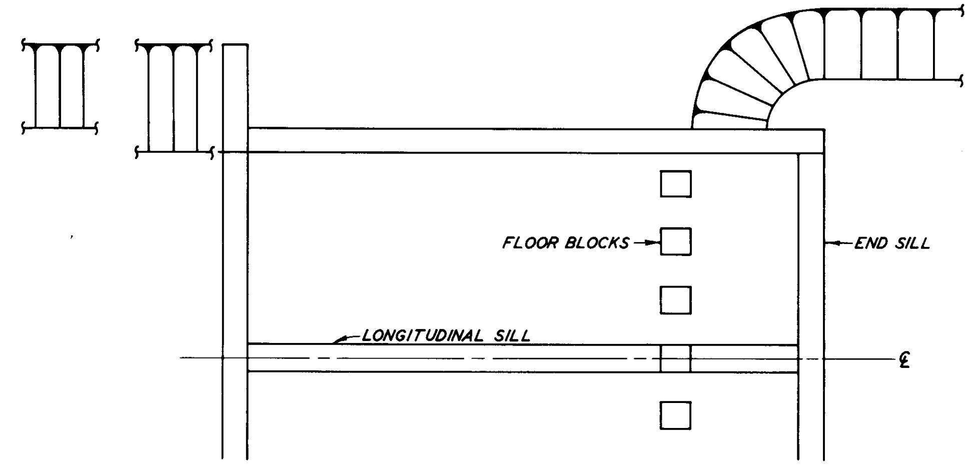
END SILL HEIGHT

SUBCRITICAL OPEN CHANNEL FLOW

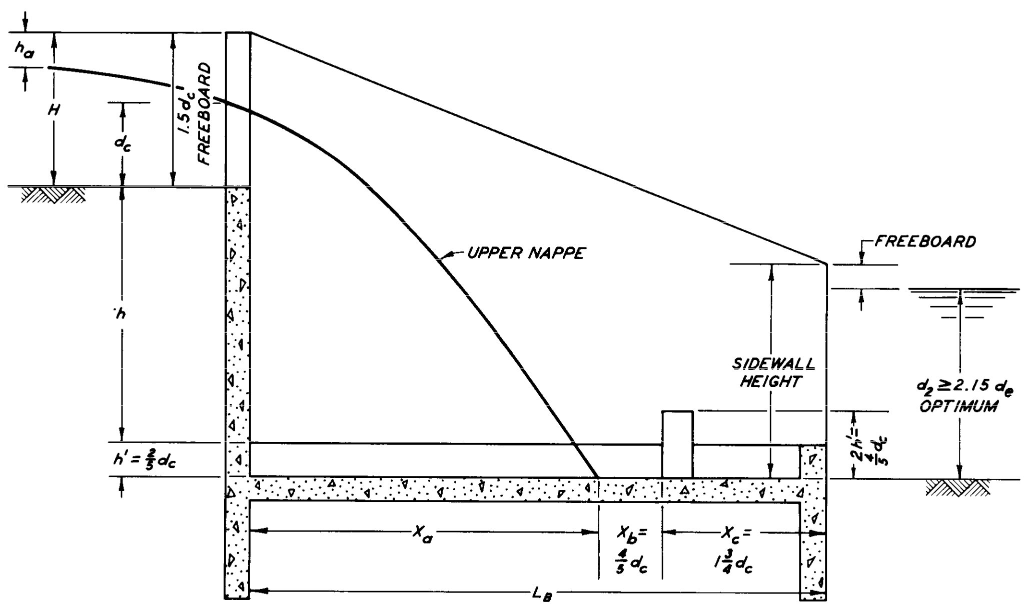
CIT-TYPE DROP STRUCTURE

HYDRAULIC DESIGN CHART 623

WES 7-73



HALF PLAN



CENTER-LINE SECTION

NOTE:

- H = HEAD ON WEIR = $\frac{3}{2}(d_c)$
- h_a = VELOCITY HEAD
- d_2 = TAILWATER DEPTH
- d_c = CRITICAL DEPTH OVER CREST
- h = HEIGHT OF DROP
- h' = HEIGHT OF END SILL
- L_B = LENGTH OF STILLING BASIN = $X_a + X_b + X_c$
- X_a = HORIZONTAL DISTANCE FROM CREST TO INTERSECTION OF UPPER NAPPE AND STILLING BASIN FLOOR
- X_b = HORIZONTAL DISTANCE FROM INTERSECTION OF UPPER NAPPE AND STILLING BASIN FLOOR TO UPSTREAM FACE OF FLOOR BLOCKS
- X_c = HORIZONTAL DISTANCE FROM UPSTREAM FACE OF FLOOR BLOCKS TO END OF STILLING BASIN

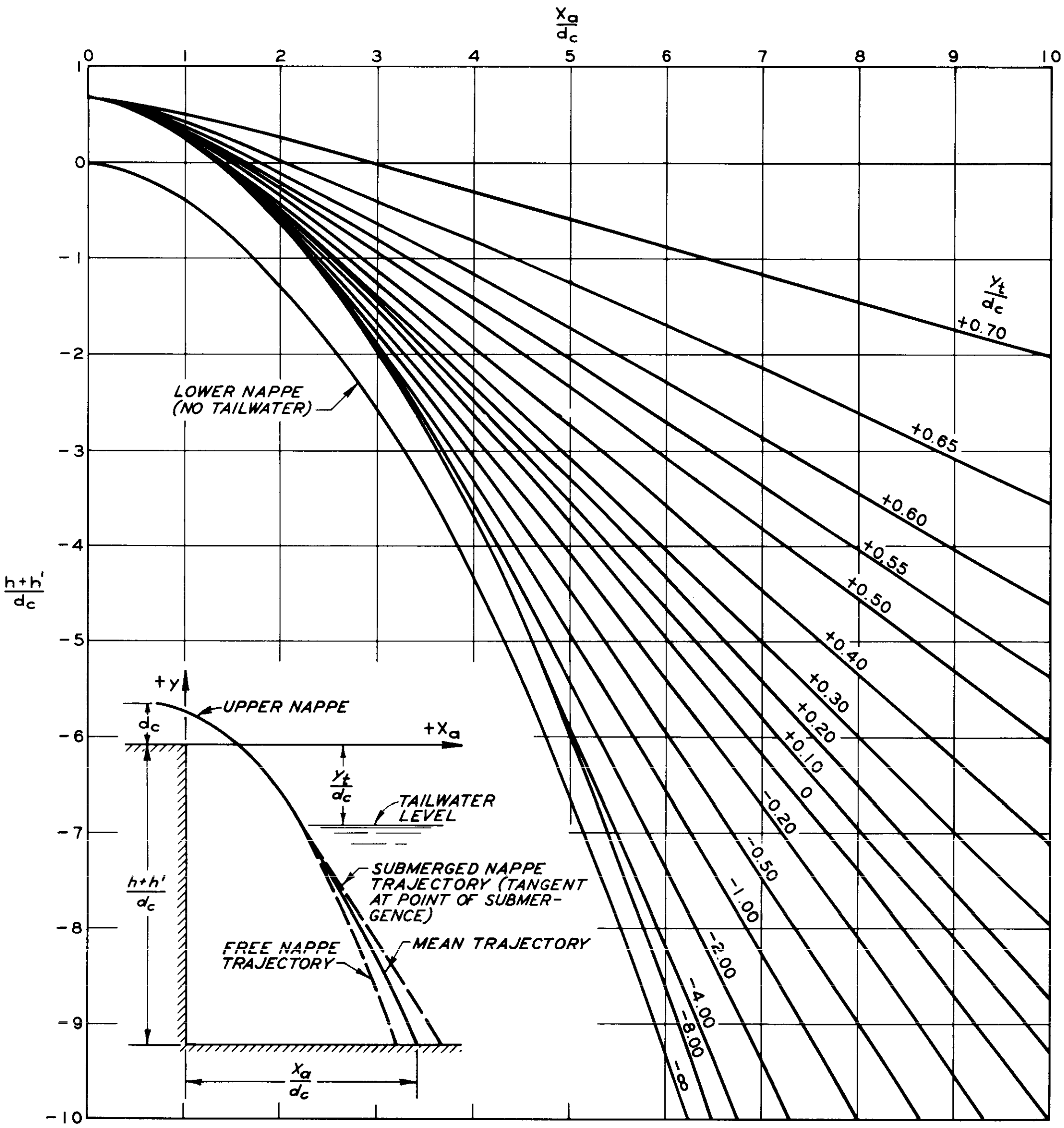
REDRAWN FROM FIG. 10, REFERENCE 4.

SUBCRITICAL OPEN CHANNEL FLOW

SAF-TYPE DROP STRUCTURE BASIC GEOMETRY

HYDRAULIC DESIGN CHART 624

WES 7-73



NOTE:

- d_c = CRITICAL DEPTH OVER CREST
- h = HEIGHT OF DROP
- h' = HEIGHT OF END SILL
- X_a = HORIZONTAL DISTANCE FROM CREST TO INTERSECTION OF UPPER NAPPE AND STILLING BASIN FLOOR
- Y_t = VERTICAL DISTANCE FROM CREST TO TAILWATER SURFACE (Y_t IS POSITIVE WHEN TAILWATER SURFACE IS ABOVE THE CREST, NEGATIVE WHEN TAILWATER SURFACE IS BELOW CREST)

REDRAWN FROM FIG. 2, REFERENCE 4.

SUBCRITICAL OPEN CHANNEL FLOW

SAF-TYPE DROP STRUCTURE JET IMPACT LOCATION

HYDRAULIC DESIGN CHART 624-1

WES 7-73

HYDRAULIC DESIGN CRITERIA

SHEETS 625-1 TO 625-1/2

DROP INTAKE STRUCTURES

1. Purpose. The purpose of these Charts is to present design criteria for rectangular drop structures upstream from steep chute channels. These criteria were developed from tests conducted at the U. S. Army Engineer Waterways Experiment Station, Vicksburg, Mississippi. Discharge calibration curves for various drop configurations are presented.

2. The general design of the structure with parameter definitions is presented on Chart 625-1. The calibration data obtained for various lengths and drops are presented on Chart 625-1/1. Drop length to chute width ratios B/W ranged from 1 to 4 and drop depth to chute width ratios D/W ranged from 0 to 1.

3. Design Criteria. The dimensions of the structure can be determined from a known discharge and allowable head or width of chute using Chart 625-1/1. All of the calibration data were obtained using an abutment radius equal to three times the width of the chute. If it becomes necessary to increase the radius of the abutments because of upstream embankments or other reasons, as probably will be the case for smaller chutes, the curve on Chart 625-1/1 labeled "D = 0" should be used for design. This design without drop will provide a conservative estimate of the discharge rating curve, and the change in the radius of abutments will have little effect on the discharge.

4. An alternate method of design has been developed by the Nashville District for design of drop intake structures on the Tennessee-Tombigbee Waterway.* The curves on Chart 625-1/2 illustrate this procedure. This form allows the direct determination of chute width for a known discharge and head.

5. These criteria apply to drop structures upstream from steep chute channels. The slope of the chute will have little effect on the drop structure discharge capacity as long as critical flow occurs within the chute. However, the length of horizontal channel shown on Chart 625-1 could cause a backwater to affect the head on the drop structure for high discharges. It is recommended that the drop structure be designed to operate with weir control or that backwater curves be computed to determine what effect this backwater will have on the head.

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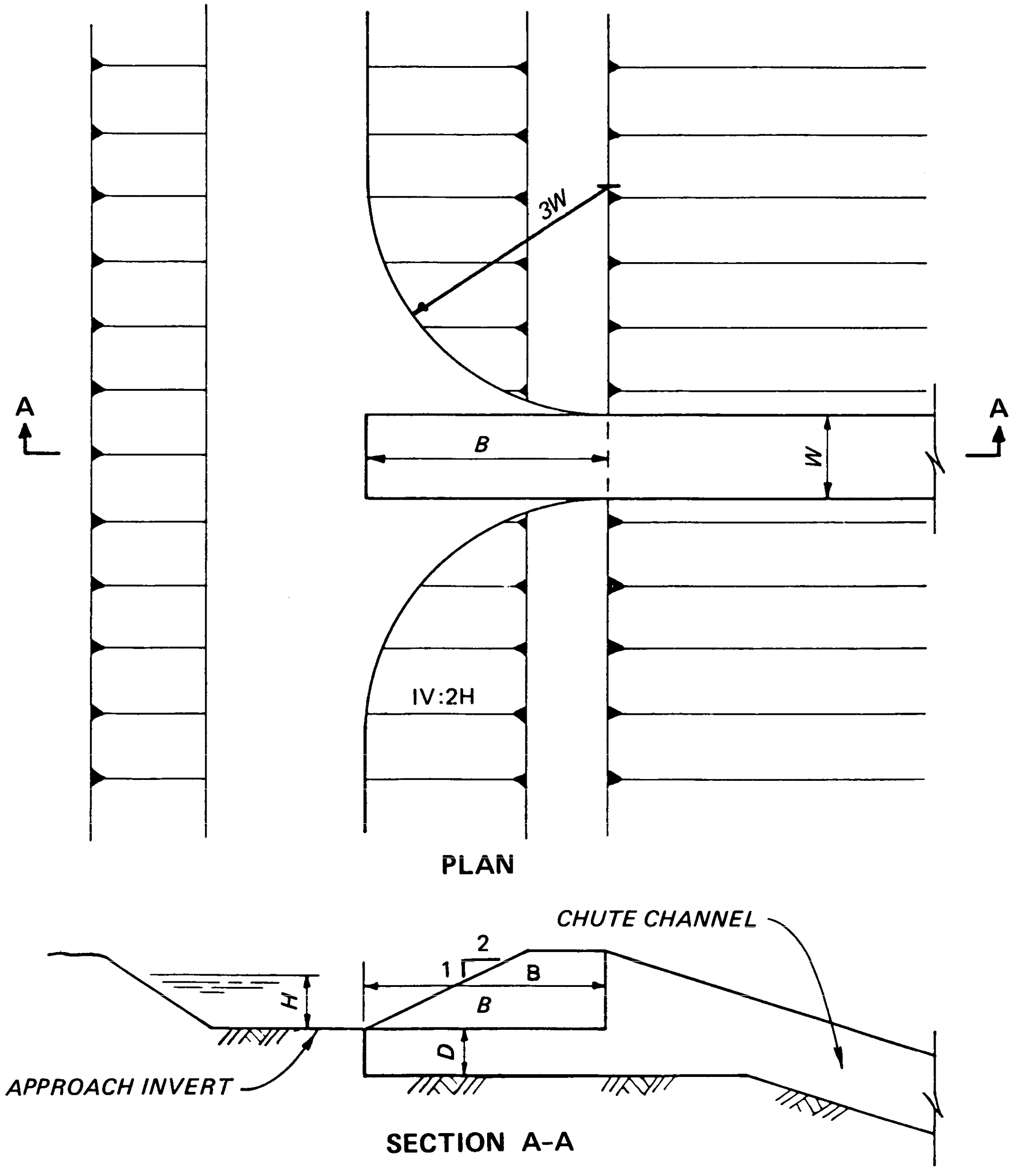
* U. S. Army Engineer Waterways Experiment Station, CE, Divide Cut Drainage Structures, Tennessee-Tombigbee Waterway, Mississippi and Alabama; Hydraulic Model Investigation, by Jackson H. Ables. Technical Report H-76-18, Vicksburg, Miss., October 1976.

6. HDC Chart 625-1/2b presents a typical drop intake structure used on the Tennessee-Tombigbee Waterway. All drop intake designs for the Tennessee-Tombigbee Waterway used a D/W ratio of 0.6 and a B/W ratio of 3.0. Drops were designed to pass an approximate 10-year discharge at a head of about 3 ft. Sidewalls were designed to pass a 25-year storm without overtopping. To date several of these structures have experienced events involving a 100-year return period rainfall without difficulty.



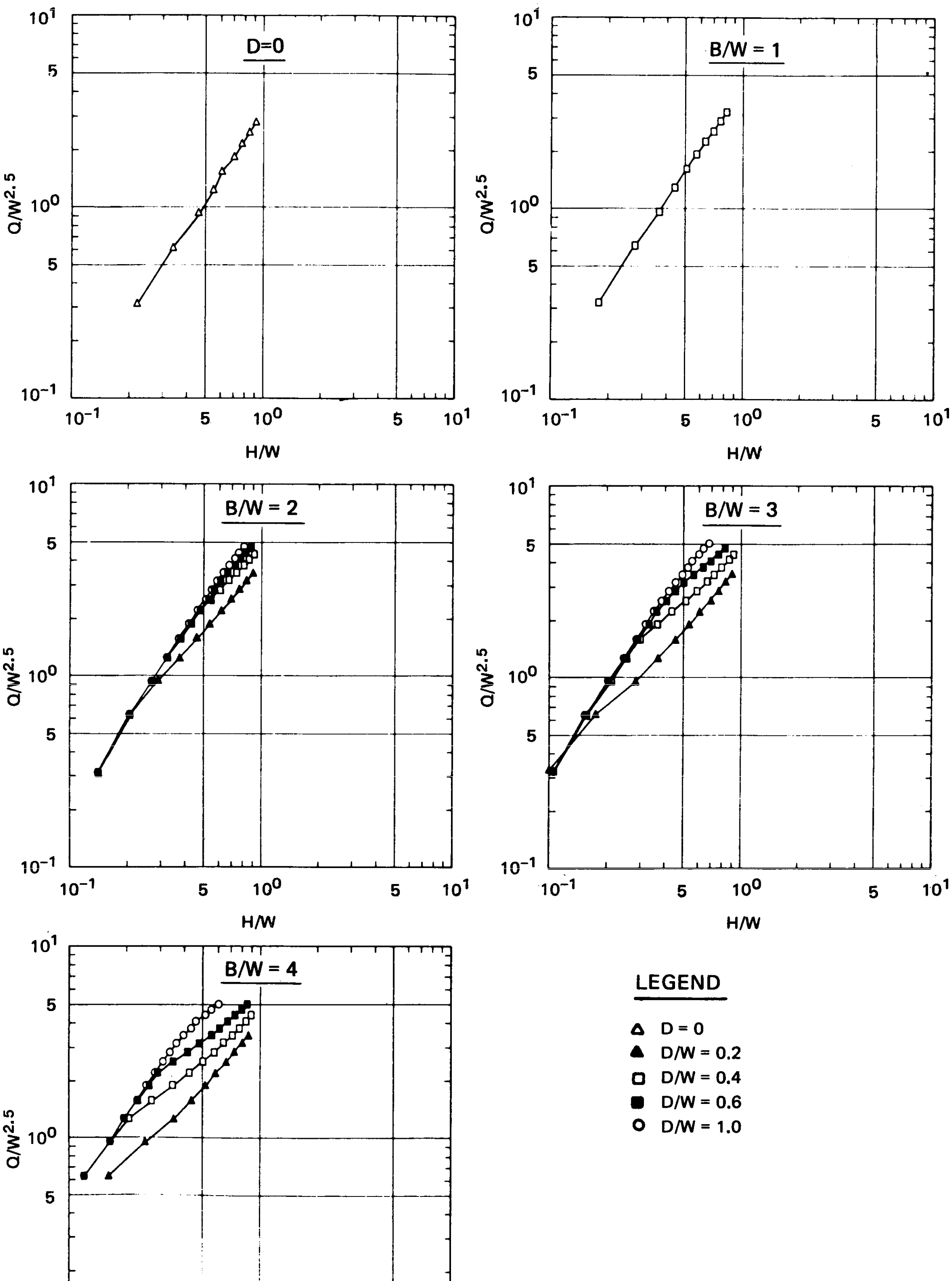
LEGEND:

B = LENGTH OF DROP, FT
D = DEPTH OF DROP, FT
W = CHUTE WIDTH, FT
H = UPSTREAM HEADWATER DEPTH, FT
Q = DISCHARGE, CFS

DROP INTAKE STRUCTURES

HDC CHART 625-1

PREPARED BY U.S. ARMY ENGINEER WATERWAYS EXPERIMENT STATION, VICKSBURG, MISSISSIPPI WES 11-87



DROP INTAKE STRUCTURES
CALIBRATION CURVES
HDC CHART 625-1/1

PREPARED BY U.S. ARMY ENGINEER WATERWAYS EXPERIMENT STATION, VICKSBURG, MISSISSIPPI WES 11-87

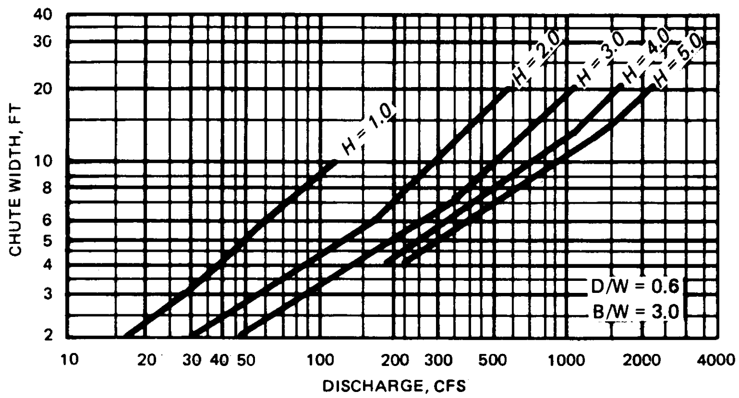
THE DISCHARGE RATING CURVE IS A TRANSFORMATION OF THE CURVE PRESENTED ON CHART 625-1/1 FOR SPECIFIED RATIOS OF B/W AND D/W.

DESIGN EXAMPLE

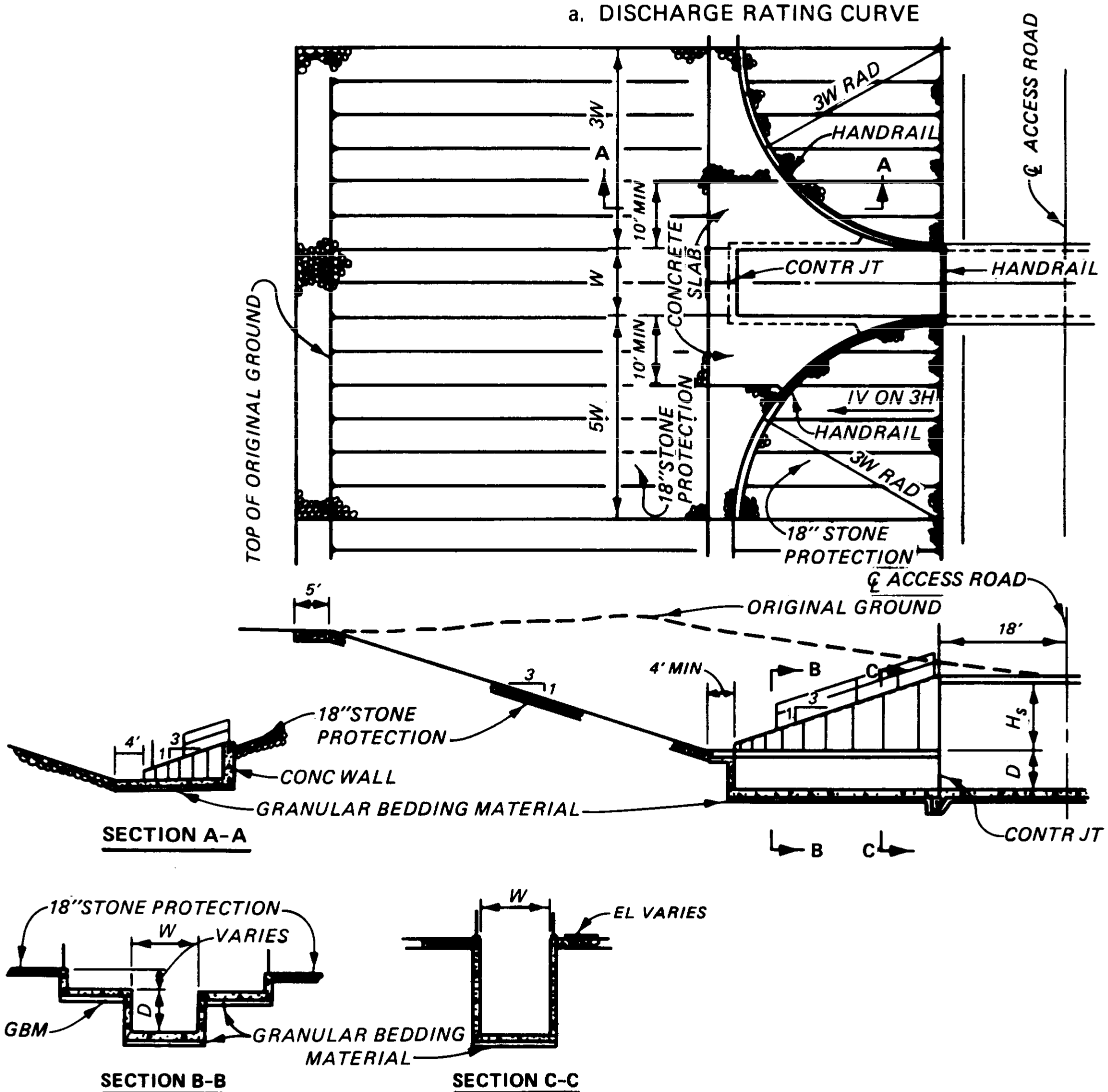
GIVEN: Q = 600 CFS
H = 2.5 FT

FOR: D/W = 0.6
B/W = 3.0

THEN: W = 15 FT
B = 45 FT
D = 9.0 FT



a. DISCHARGE RATING CURVE



b. TYPICAL DESIGN, TENNESSEE-TOMBIGBEE WATERWAY

DROP INTAKE STRUCTURE
TYPICAL DESIGN
HDC CHART 625-1/2

HYDRAULIC DESIGN CRITERIA

SHEETS 631 TO 631-2

OPEN CHANNEL FLOW

RESISTANCE COEFFICIENTS

1. General. Because of its simplicity, the Manning equation has been used extensively in the United States in the evaluation of resistance losses in open channel flow. A comprehensive summary of the use of this equation in channel design is given in reference 1. Flow data and Manning's n's for 50 natural streams, together with color photographs of the channels, have also been published.[2] The Chezy equation[1] includes a resistance coefficient term that is applicable to all flow conditions. Hydraulic Design Chart 631 presents a general resistance diagram relating Chezy's C, Reynolds number, and relative roughness. The chart is useful in open channel flow problems.

2. Laboratory and field investigations have shown that the resistance coefficient varies with Reynolds numbers as well as with boundary surface roughness. Keulegan[3] has demonstrated that the Von Karman-Prandtl smooth and rough pipe resistance equations based on the Nikuradse test data can be applied to open channel flow with only minor adjustments in the equation constants. A recent ASCE progress report[4] recommends a Moody-type diagram for use in open channel flow, especially for flows in which the viscous effects are important.

3. Chezy Equation. The Chezy equation is

$$V = C\sqrt{RS}$$

where

V = mean channel velocity, ft per sec

C = Chezy resistance coefficient which is a function of Reynolds number and relative roughness of channel

R = hydraulic radius of channel, ft

S = slope of energy gradient

4. Resistance Coefficient Relations. The Darcy resistance coefficient f (see Hydraulic Design Chart 224-1) is defined as

$$f = \frac{8RSg}{V^2}$$

where g = acceleration of gravity.

The relation between C and f is

$$C = \sqrt{\frac{8g}{f}}$$

Similarly, the relation of C and n can be shown to be

$$C = \frac{1.486R^{1/6}}{n}$$

5. Effects of Reynolds Number. The Chezy resistance coefficient C is plotted as a function of Reynolds number in Chart 631. An auxiliary scale of Darcy resistance coefficient f is also shown for alternative use by the designer. The method of plotting is a form of the Moody diagram (Sheet 224-1). The resistance equations for smooth and rough flow based on Keulegan's results and recommended by Chow[1] are given and plotted in Chart 631. The rough flow limit based on Rouse's pipe flow criterion[5] is also shown. The Keulegan constants were used in the Colebrook-White equation (Chart 224-1) for the transition flow zone. The Reynolds number used for plotting is

$$R_e = \frac{4VR}{\nu}$$

where ν = the kinematic viscosity.

The use of this form of the Reynolds number is recommended in the ASCE task force report.[4]

6. Basic Data. The plotted data in Chart 631 are for concrete-lined channels. Both tranquil- and rapid-flow data are presented. The tranquil-flow data were computed from U. S. Army Engineer Waterways Experiment Station (WES) laboratory tests in brushed-concrete flumes[6,7] and from field tests results compiled by Scobey.[8,9] More recently obtained U. S. Bureau of Reclamation (USBR)[10] and Italian[11] field data have also been included. These data were selected on the basis of accuracy of flow measurements and conditions of concrete channel lining. Tests at the University of Iowa[12] indicate that the energy loss in flows having Froude numbers greater than 1.6 becomes a function of the Froude number and density and size of roughness elements. Additional energy loss is caused by instability of the flow. The plotted data points based on prototype tests at the Fort Randall[13] and Fort Peck[14] spillway chutes are for rapid flow with Froude numbers exceeding the stability criterion. These data represent the only known available measurements at R_e numbers approaching 10^8.

7. Suggested Design Criteria.

a. Resistance coefficients. The data plotted in Chart 631 can be used for guidance in the design of concrete-lined channels with subcritical velocities. Resistance coefficients for these channels generally are in the transition zone shown in the chart. The flow regime is seldom hydraulically smooth or fully rough and the resistance coefficient is usually a function of both the Reynolds number and the relative roughness. Chart 631-1 is a plot relating Chezy C, Manning's n, the equivalent roughness k_s, and the hydraulic radius. Theoretically it is only applicable to rough flow conditions. This chart should be useful for relating C and n for the design of channels with riprapped banks (Charts 631-4 and 631-4/1). The equation for n on Chart 631-1 was developed by solving the rough flow equation given in Chart 631 in terms of Manning's n.

b. Equivalent roughness k_s. In the use of Chart 631, a value of k_s (equivalent sand grain diameter) has to be specified for the prediction of resistance. The hydraulic roughness k_s in pipe flow is dependent only on the type of construction or the surface finish specified. However, in open channel flow it includes the effects of secondary flow resulting from boundary geometry and to a lesser extent the free water surface. Experimental data for correlation of surface texture, channel geometry, and the resulting hydraulic equivalent roughness k_s are very limited. However, considerable variation in the selected k_s value results in only small changes in the flow energy loss.

(1) The following tabulation presents average k_s values resulting from different types of concrete forming and surface finishing. It is based on computations made from the open channel resistance data plotted in Chart 631.

Average k_s, ft	Concrete Surface Finish
0.0006	18-year-old, 10-ft-wide rectangular aqueduct. Troweled sides and float-finished bottom (ref 9)
0.002	Laboratory rectangular and trapezoidal channels, brushed concrete finish (refs 6 and 7). Field channels, smooth, troweled cement finish (refs 8, 9, and 11)

(Continued)

Average k_s, ft	Concrete Surface Finish
0.003	10- to 20-year-old, 8- to 50-ft-wide trapezoidal channels constructed with modern rail-mounted slip traveling forms (ref 10)
0.005	Screed-finished spillway chute blocks with transverse joints at 20- to 25-ft intervals (refs 13 and 14)

(2) The tabulation above can be used for selecting design k_s values if the concrete forming and surface finishing can be obtained with good assurance. For general design computations the following k_s values for concrete are suggested:

Design Problem	Suggested k_s Value, ft
Discharge capacity	0.007
Maximum velocity	0.002
Proximity to critical depth*	
Subcritical flow	0.002
Supercritical flow	0.007

* To prevent undesirable undulating waves, flow-depth-to-critical depth ratios between 0.9 and 1.1 should be avoided.

(3) The determination of the equivalent surface roughness for riprap channels, rubble masonry, or other large roughness protrusions should be based on some estimate of the mean protrusion, riprap, or rock size. Use of the D_{50} (mean) size as k_s, based on equivalent sphere weight, is a good approximation for stone riprap.

8. Application. Chart 631-2 is a sample computation sheet illustrating the use of Charts 631 and 631-1.

9. References.

(1) Chow, V. T., Open-Channel Hydraulics. McGraw-Hill Book Co., Inc., New York, N. Y., 1959, pp 109-123.

(2) U. S. Geological Survey, Roughness Characteristics of Natural Channels, by H. H. Barnes, Jr. Water-Supply Paper 1849, Washington, D. C., 1967.

(3) Keulegan, G. H., "Laws of turbulent flow in open channels." Journal of Research, National Bureau of Standards, vol 21, Research Paper No. 1151 (December 1938), pp 707-741.

(4) Progress Report of the Task Force on Friction Factors in Open Channels, "Friction factors in open channels." ASCE, Hydraulics Division, Journal, vol 89, HY 2, paper 3464 (March 1963), pp 97-143.

(5) Rouse, H., Engineering Hydraulics; Proceedings of the Fourth Conference, Iowa Institute of Hydraulic Research, June 12-15, 1949. John Wiley & Sons, Inc., New York, N. Y., 1950, p 404.

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(7) __________, Hydraulic Capacity of Meandering Channels in Straight Floodways; Hydraulic Model Investigation, by E. B. Lipscomb. Technical Memorandum No. 2-429, Vicksburg, Miss., March 1956.

(8) U. S. Department of Agriculture, The Flow of Water in Flumes, by F. C. Scobey. Technical Bulletin No. 393, Washington, D. C., December 1933.

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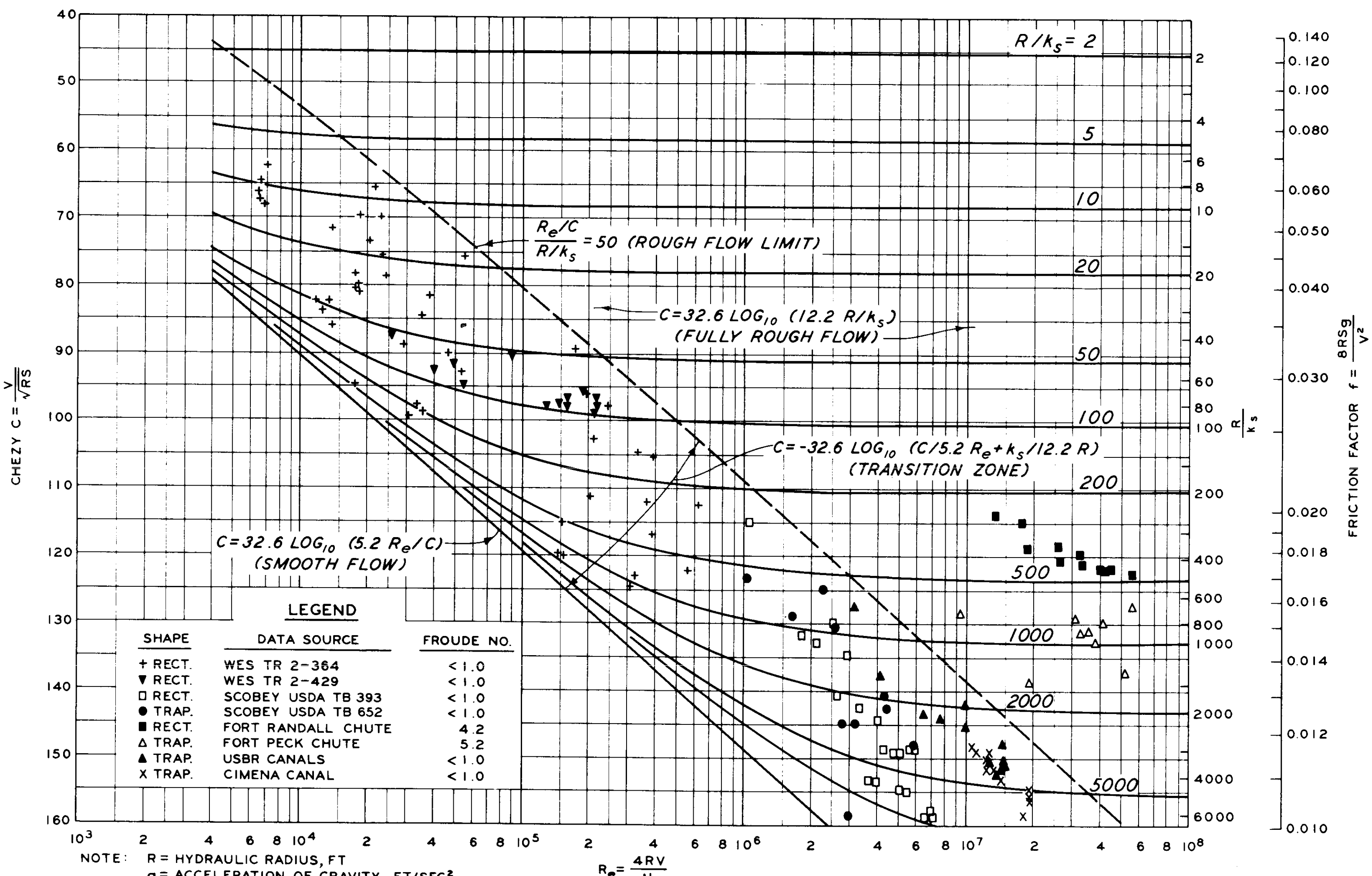
(10) U. S. Bureau of Reclamation, Analyses and Descriptions of Capacity Tests in Large Concrete-Lined Canals, by P. J. Tilp and M. W. Scrivner. Technical Memorandum 661, Denver, Colo., April 1964.

(11) Grassino, R., "Determination of roughness coefficients for Cimena Canal." L'Energia Elettrica, vol XL, No. 6 (June 1963), pp 429-436. Translation by Jan C. Van Tienhoven for U. S. Army Engineer Waterways Experiment Station, CE, Translation No. 65-3, Vicksburg, Miss., May 1965.

(12) Rouse, H., Koloseus, H. J., and Davidian, J., "The role of the Froude number in open-channel resistance." Hydraulic Research, Journal of the International Association for Hydraulic Research, vol 1, No. 1 (1963), pp 14-19.

(13) U. S. Army Engineer Waterways Experiment Station, CE, Flow in Chute Spillway at Fort Randall Dam; Hydraulic Prototype Tests, by C. J. Huval. Technical Report No. 2-716, Vicksburg, Miss., April 1966.

(14) U. S. Army Engineer District, Omaha, Nebraska. (Unpublished memorandum on Fort Peck Spillway tests, 1951.)



LEGEND

SHAPE	DATA SOURCE	FROUDE NO.
+ RECT.	WES TR 2-364	< 1.0
▼ RECT.	WES TR 2-429	< 1.0
□ RECT.	SCOBEY USDA TB 393	< 1.0
● TRAP.	SCOBEY USDA TB 652	< 1.0
■ RECT.	FORT RANDALL CHUTE	4.2
△ TRAP.	FORT PECK CHUTE	5.2
▲ TRAP.	USBR CANALS	< 1.0
X TRAP.	CIMENA CANAL	< 1.0

NOTE: R = HYDRAULIC RADIUS, FT
g = ACCELERATION OF GRAVITY, FT/SEC²
ν = KINEMATIC VISCOSITY, FT²/SEC
k_s = EFFECTIVE ROUGHNESS HEIGHT, FT
V = VELOCITY, FT/SEC
S = ENERGY GRADIENT SLOPE
R_e = REYNOLDS NUMBER

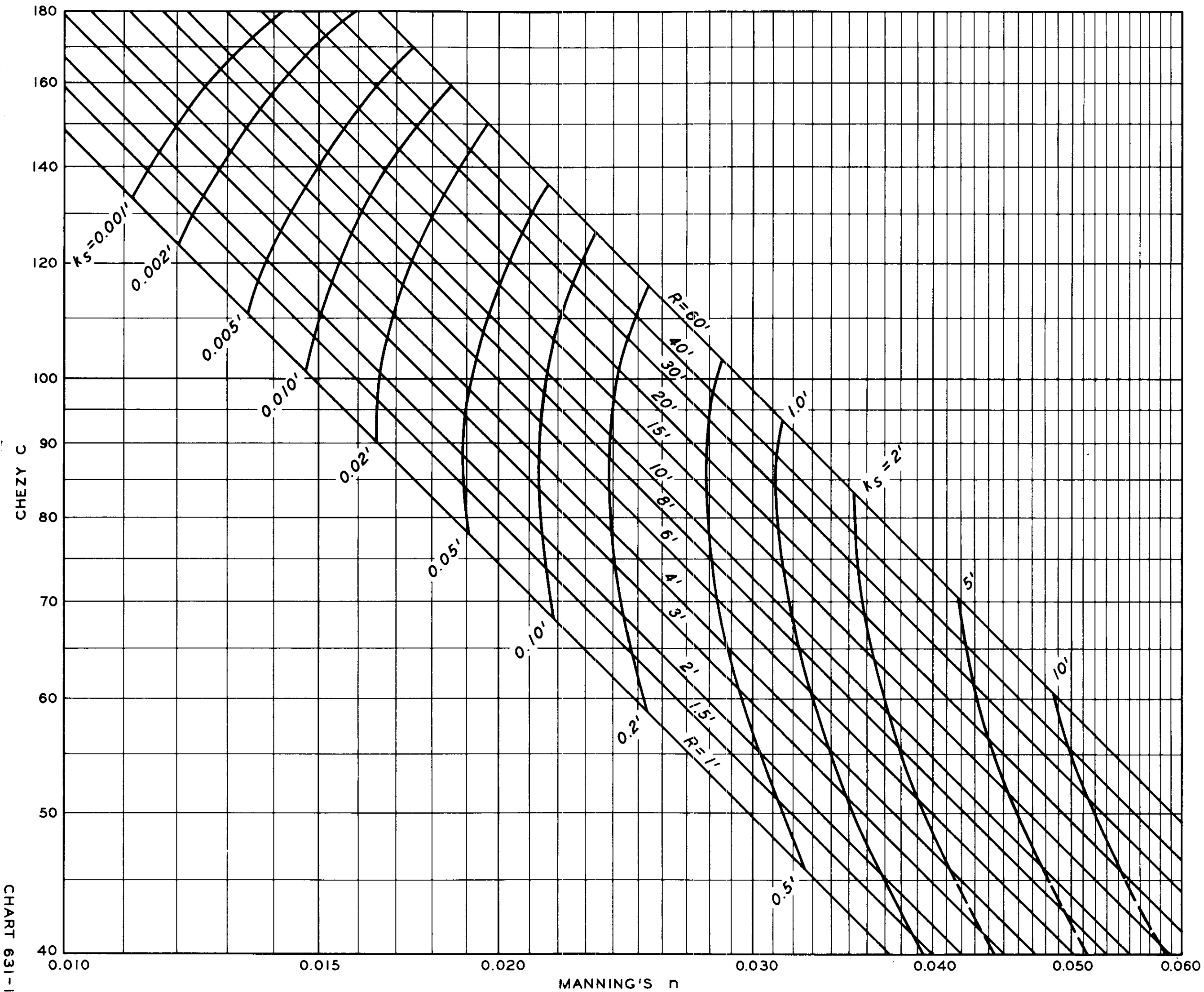
OPEN CHANNEL FLOW
RESISTANCE COEFFICIENTS

HYDRAULIC DESIGN CHART 631

REV 1-68

WES 8-58

PREPARED BY U. S. ARMY ENGINEER WATERWAYS EXPERIMENT STATION, VICKSBURG, MISSISSIPPI



BASIC EQUATIONS

$$C = 32.6 \log_{10} 12.2 R/k_s$$

$$n = \frac{R^{1/6}}{23.85 + 21.95 \log_{10} R/k_s}$$

WHERE:

- C = CHEZY COEFFICIENT
- n = MANNING'S RESISTANCE COEFFICIENT
- R = HYDRAULIC RADIUS, FT
- k_s = EFFECTIVE ROUGHNESS HEIGHT, FT

OPEN CHANNELS

C-n-R-k_s RELATION

HYDRAULIC DESIGN CHART 631-1

REV 1-68 WES 8-58

PREPARED BY U. S. ARMY ENGINEER WATERWAYS EXPERIMENT STATION, VICKSBURG, MISSISSIPPI

GIVEN:

Concrete-lined channel
Shape, trapezoidal
Invert slope (S) = 0.0004
Flow depth (D) = 12 ft
Side slope = 1 on 2
Water temperature = 60 F
Discharge (Q) = 15,000 cfs
Construction, rail-mounted traveling forms

REQUIRED:

Equivalent roughness k_s
Chezy C
Base width B
Froude No. < 0.85
Check Manning's n

From tabulation of equivalent roughness (par. 7b(1), Sheets 631 to 631-2), $k_s = 0.003$ ft
From Chart 001-1, $\nu = 1.22 \times 10^{-5}$ ft^2/sec at 60 F

TRIAL COMPUTATIONS

1. Assume base width B = 50 ft

$$V = \frac{Q}{\text{Area}} = \frac{15{,}000}{74 \times 12} = 16.9 \text{ ft/sec}$$

$$\text{Hydraulic radius } R = \frac{\text{Area}}{\text{Wetted Perimeter}} = \frac{74 \times 12}{103.6} = 8.57 \text{ ft}$$

$$R_e = \frac{4VR}{\nu} = \frac{4(16.9)(8.57)}{1.22 \times 10^{-5}} = 4.75 \times 10^7$$

$$\frac{R}{k_s} = \frac{8.57}{0.003} = 2860 \qquad C = 148 \text{ (Chart 631)}$$

$$V = C\sqrt{RS} = 148\sqrt{8.57 \times 0.0004} = 8.67 \text{ ft/sec} < 16.9 \text{ ft/sec}$$

2. Assume base width B = 110 ft

$$V = \frac{15{,}000}{134 \times 12} = 9.33 \text{ ft/sec} \qquad R = \frac{134 \times 12}{163.6} = 9.83 \text{ ft}$$

$$R_e = \frac{4(9.33)(9.83)}{1.22 \times 10^{-5}} = 3.0 \times 10^7$$

$$\frac{R}{k_s} = \frac{9.83}{0.003} = 3280 \qquad C = 149 \text{ (Chart 631)}$$

$$V = 149\sqrt{9.83 \times 0.0004} = 9.34 \approx 9.33 \text{ ft/sec}$$

3. Check Froude No. (F) and Manning's n

$$F = \frac{V}{\sqrt{gD}} \text{ (wide channel)} = \frac{9.33}{\sqrt{g(12)}} = 0.48 < 0.85$$

$$n = 0.0145 \text{ (Chart 631-1)}$$

OPEN CHANNEL FLOW
RESISTANCE COEFFICIENTS
SAMPLE COMPUTATION

HYDRAULIC DESIGN CHART 631-2

HYDRAULIC DESIGN CRITERIA

SHEETS 631-4 AND 631-4/1

OPEN CHANNEL FLOW

COMPOSITE ROUGHNESS

EFFECTIVE MANNING'S n

1. Tables of recommended roughness coefficients for use in the Manning formula for the solution of open channel flow problems have been published in references 1 and 2. Chow[2] includes recommended values for channels having different bed and bank materials. In wide, shallow channels the bed roughness effects predominate. Conversely, in narrow deep channels the bank roughness is the primary factor contributing to the flow energy losses.

2. Basic Data. Procedures for computing the effective roughness coefficient n to be used in the Manning formula for channels with different bed and bank roughnesses have been developed by Horton,[3] Colebatch,[4] Einstein,[5] and the U. S. Army Engineer District, Los Angeles, California.[6] In each case the effective n value is a function of the bed and bank roughnesses and their respective segments of the wetted perimeter or flow area. In their simplest form, the equations for effective n values can be written as

$$n_{eff} = \frac{\Sigma nA}{\Sigma A} \qquad \text{(Los Angeles District)} \qquad (1)$$

$$n_{eff} = \left[\frac{\Sigma(n^{3/2}\ P)}{P}\right]^{2/3} \qquad \text{(Horton or Einstein)} \qquad (2)$$

$$n_{eff} = \left[\frac{\Sigma(n^{3/2}\ A)}{\Sigma A}\right]^{2/3} \qquad \text{(Colebatch)} \qquad (3)$$

A and P are the channel flow subareas and wetted perimeter segments, respectively; n is the respective Manning roughness coefficient for each segment considered.

3. Study of the equations given in paragraph 2 indicates that for channels with smooth inverts and rough banks, use of the Horton-Einstein equation results in more conservative design than use of either the Colebatch or the Los Angeles District equation. Laboratory and field investigations are needed for complete evaluation of the equations. The use of the Horton-Einstein equation is suggested for design purposes pending availability of additional test data.

4. For rectangular or trapezoidal channels, equation 2 can be written in the form

$$n_{eff} = \left(\frac{n_1^{3/2} P_1 + 2n_2^{3/2} P_2}{P_1 + 2P_2} \right)^{2/3} \qquad (4)$$

where the subscripts 1 and 2 refer to the bed and bank wetted perimeters, respectively. The terms are further defined in the sketch in Hydraulic Design Chart 631-4/1.

5. Application. Chart 631-4 provides a rapid graphical method for determining the solution of equation 2 to obtain an effective n value for use in the design of uniform channel sections with different bed and bank roughnesses. The ordinates of the chart indicate the bed, bank, and combined effective roughness coefficients. The abscissas are values of the ratio of the bed and bank wetted perimeters. The effective n value is determined in the following manner. The chart is entered vertically from the bottom with the given value of $2P_2/P_1$ to its intersection with an imaginary line connecting n_1 and n_2. The value of n_{eff} at this point is read on the right side of the chart.

6. Chart 631-4/1 can be used to obtain the required wetted perimeter ratio for use with Chart 631-4. Chart 631-4/1 presents bank-bed wetted perimeter relations for trapezoidal and rectangular channel sections as functions of the bed width, flow depth, and bank slope. These charts can be used with Charts 631 and 631-1 for the design of channels with riprapped banks.

7. References.

(1) King, H. W., Handbook of Hydraulics for the Solution of Hydraulic Problems, revised by E. F. Brater, 4th ed. McGraw-Hill Book Co., Inc., New York, N. Y., 1954, Table 76, p 20.

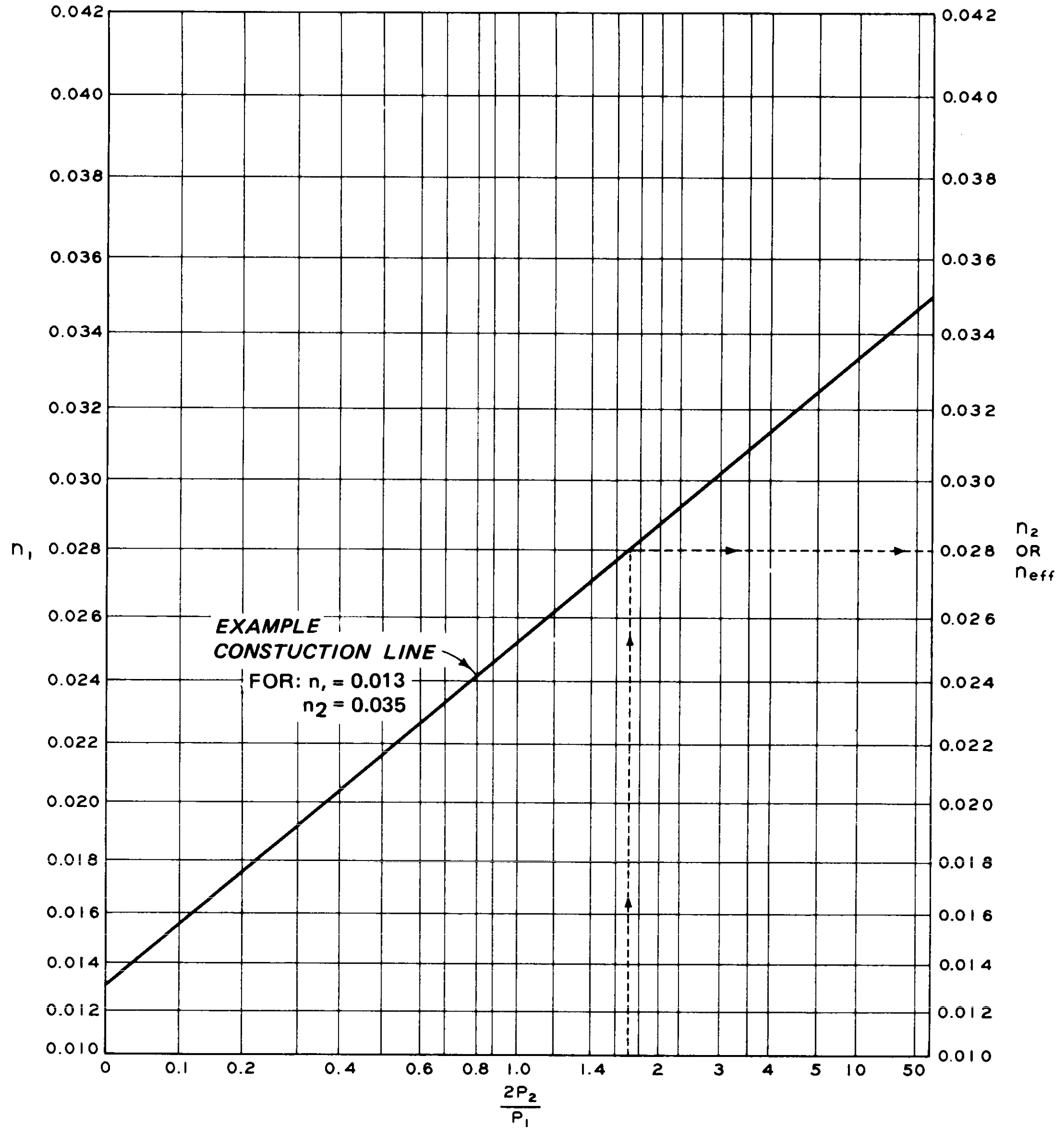
(2) Chow, V. T., Open-Channel Hydraulics. McGraw-Hill Book Co., Inc., New York, N. Y., 1959, Tables 5 and 6, p 111.

(3) Horton R. E., "Separate roughness coefficients for channel bottom and sides." Engineering News-Record, vol iii, No. 22 (30 November 1933), pp 652-653.

(4) Colebatch, G. T., "Model tests on Liawenee Canal roughness coefficients." Transactions of the Institution, Journal of the Institution of Engineers, vol 13, No. 2, Australia (February 1941), pp 27-32.

(5) Einstein, H. A., "Der hydraulische oder Profil-Radius." Schweizerische Bauzeitung, vol 103, No. 8 (24 February 1934), pp 89-91.

(6) U. S. Army, Office, Chief of Engineers, Hydraulic Design of Flood Control Channels. EM 1110-2-1601 (unpublished Engineer Manual draft).



EFFECTIVE MANNING'S n (EQUATION 4)

$$n_{eff} = \left(\frac{n_1^{3/2} P_1 + 2 n_2^{3/2} P_2}{P_1 + 2P_2} \right)^{2/3}$$

WHERE:

n_1 = BED ROUGHNESS
n_2 = SIDE SLOPE ROUGHNESS
n_{eff} = EFFECTIVE ROUGHNESS
P_2 = SIDE SLOPE WALL LENGTH
P_1 = BOTTOM WIDTH

NOTE: GRAPH BASED ON FIGURE 8, REF 4

OPEN CHANNEL FLOW

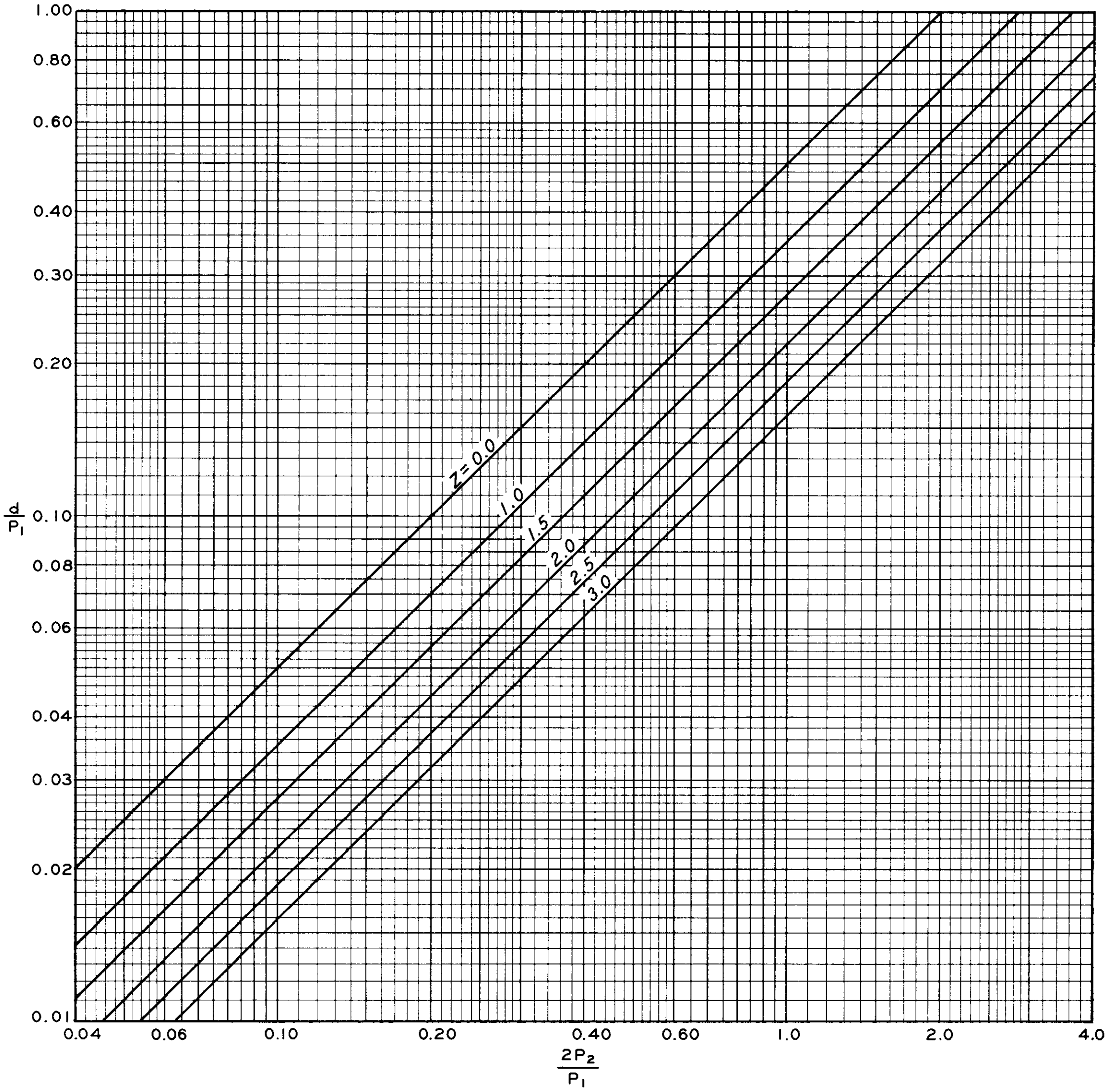
COMPOSITE ROUGHNESS
EFFECTIVE MANNING'S n

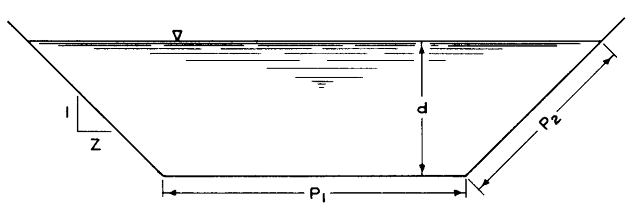
HYDRAULIC DESIGN CHART 631-4

REV 11-87

WES 1-68

PREPARED BY U. S. ARMY ENGINEER WATERWAYS EXPERIMENT STATION, VICKSBURG, MISSISSIPPI





$P_2 = d\sqrt{1+Z^2}$

OPEN CHANNEL FLOW

COMPOSITE ROUGHNESS
WETTED PERIMETER RELATION

HYDRAULIC DESIGN CHART 631-4/1

WES 1-68

PREPARED BY U. S. ARMY ENGINEER WATERWAYS EXPERIMENT STATION, VICKSBURG, MISSISSIPPI

HYDRAULIC DESIGN CRITERIA

SHEET 660-1

CHANNEL CURVES

SUPERELEVATION

1. Purpose. Flows in curved channels result in increases in depth along the outside channel walls with corresponding decreases along the inside walls. The difference in the water-surface elevations between the channel center line and the outside wall is called the flow superelevation. This rise in water surface is a function of the channel shape, velocity, width, and radius of curvature. Chart 660-1 presents a graphical means of estimating superelevation for various combinations of channel velocities, widths, and radii of curvature.

2. Design Controls. Channel capacity (wall heights) should be based on the maximum expected resistance (friction) factor. The curve geometry and flow superelevation should be based on the minimum expected resistance factor. This design combination should result in economically conservative design for all flows.

3. Design Equations. The transverse rise in water surface of flow in a channel bend can be adequately described for both tranquil and rapid flow using an equation adapted from the centrifugal force equations.

$$\Delta y = C \frac{V^2 W}{gr} \tag{1}$$

where

Δy = the rise (superelevation plus surface disturbances) in water surface between the channel center line and the outside wall, ft

C = a coefficient depending upon flow Froude number, channel shape, and curve geometry

V = average channel velocity, fps

W = straight channel water-surface width, ft

g = acceleration of gravity, ft/sec^2

r = radius of curvature at center line, ft

The following tabulation relates the coefficient C with flow conditions, channel shape, and curve geometry. These relations are also shown by the sketches in Chart 660-1.

Type of Flow	Channel Shape	Curve Geometry	Coefficient C Value
Tranquil	Rect	Simple	0.5
Tranquil	Trap.	Simple	0.5
Rapid	Rect	Simple	1.0
Rapid	Trap.	Simple	1.0
Rapid	Rect	Spiral transition	0.5
Rapid	Trap.	Spiral transition	1.0
Rapid	Rect	Spiral-banked	0.5

4. Curve Design.

a. Tranquil flow. The required increase in the outer wall height in a channel curve over that of the straight channel for both rectangular and trapezoidal channels is obtained from Chart 660-1 using a C value of 0.5. The inner wall height should remain that of the straight channel. The unbalanced flow condition in the curve causes helicoidal flow that can result in undesirable scour and deposition in and downstream from the curve. Tests by Shukry[1] indicate that helicoidal flow can be minimized if the curve radius is greater than three times the channel width.

b. Rapid flow. Rapid flow in a simple circular curve results in a transverse rise in the water surface approximately twice that occurring with tranquil flow. This increase results from surface disturbances generated by changes in direction. These disturbances persist for many channel widths downstream of the curve. Superelevation for rapid flow can be estimated from Chart 660-1 using the appropriate C values given in the tabulation above or in the chart. A detailed analysis of the cross waves generated in simple curves is given by Ippen.[2]

The criterion for minimum radius of a simple curve, based on structures built by the Los Angeles District, is:

$$r_{min} = \frac{4V^2W}{gy} \tag{2}$$

with y equal to the flow depth for the minimum expected friction factor (Chart 631). This criterion is recommended for rapid flow curves with or without invert banking. A similar criterion for maximum allowable superelevation for acceptable flow conditions in rectangular channels is

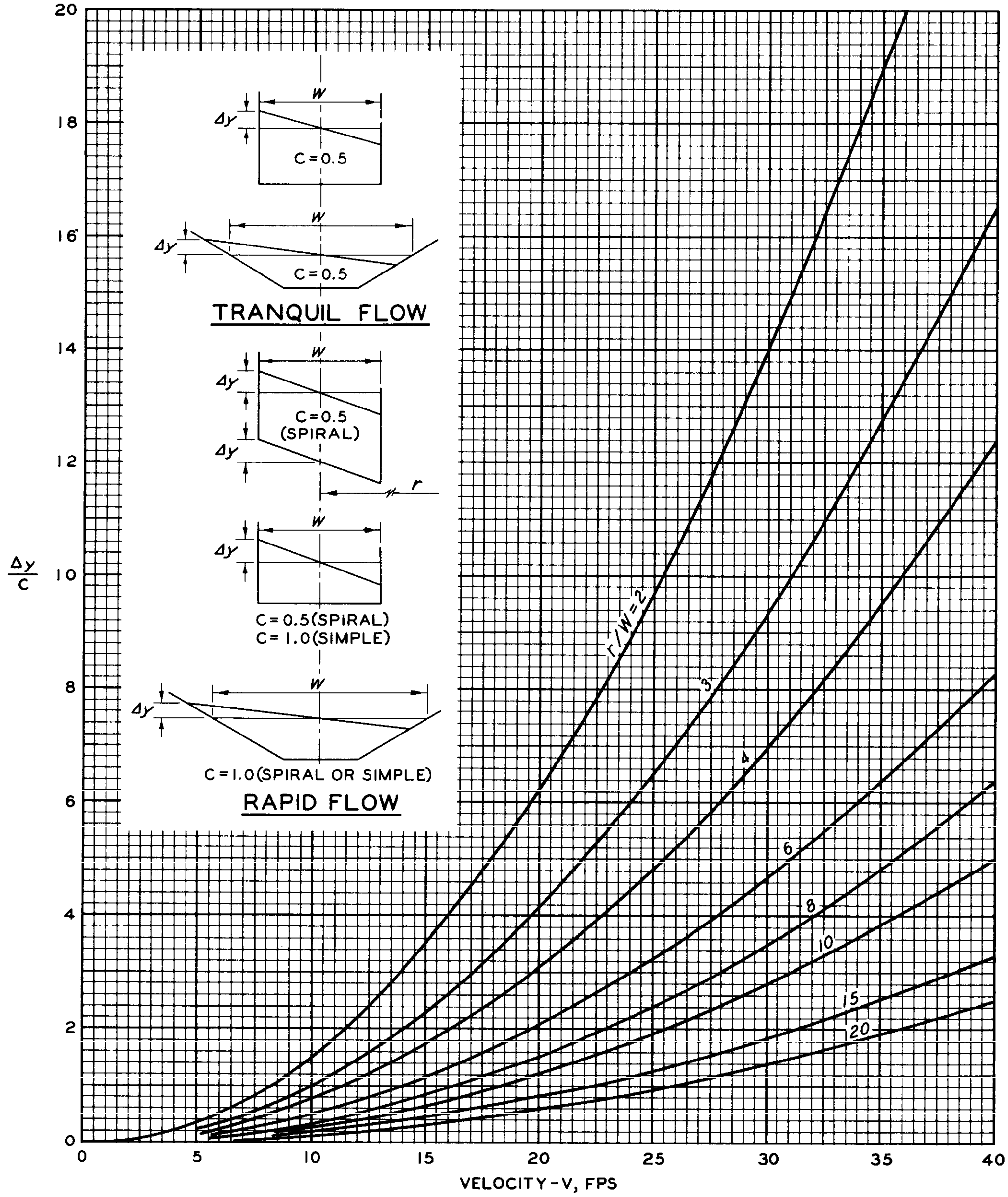
$$\Delta y_{max} = 0.09W \tag{3}$$

c. Invert banking. Invert banking maintains flow stability in curved channels and when used with spiral transitions results in minimum total rise in water surface between the channel center line and outside wall. It is limited to channels of rectangular cross sections. The invert is usually banked by rotating the bottom about the channel center line. The invert along the inside wall is depressed by Δy below the center-line elevation with a corresponding rise along the outside wall. The banking upstream and downstream from the curve should be accomplished linearly in accordance with the spiral transition lengths determined from equation 3 of Sheets 660-2 to 660-2/4. Wall heights on both sides of banked curves are usually designed to be the same as the wall height of the straight channel. Banking of trapezoidal channels is not practicable. Such channels should be designed wherever possible to have long radius curves resulting in minimum superelevation.

5. References.

(1) Shukry, A., "Flow around bends in an open flume." Transactions, American Society of Civil Engineers, vol 115, paper 2411 (1950), pp 751-779.

(2) Ippen, A. T., "Channel transitions and controls," Engineering Hydraulics, H. Rouse, ed. John Wiley & Sons, Inc., New York, N. Y., 1950, pp 496-588.



EQUATION

$$\Delta y = C \frac{V^2}{g} \frac{W}{r}$$

WHERE:

- V = AVERAGE VELOCITY
- Δy = SUPERELEVATION
- W = WATER SURFACE WIDTH (LEVEL)
- r = CURVE RADIUS
- C = CONSTANT
- g = GRAVITATIONAL ACCELERATION

CHANNEL CURVES

SUPERELEVATION

HYDRAULIC DESIGN CHART 660-1

PREPARED BY U. S. ARMY ENGINEER WATERWAYS EXPERIMENT STATION, VICKSBURG, MISSISSIPPI

WES 9-70

HYDRAULIC DESIGN CRITERIA

SHEETS 660-2 TO 660-2/4

CHANNEL CURVES WITH

SPIRAL TRANSITIONS

RAPID FLOW

1. Purpose. Spiral transitions are used to provide gradual change in channel curvature for rapid flow entering and leaving circular bends.[1] The compound circular curve has also been used for this purpose.[2] Use of spiral transitions eliminates the surface disturbances discussed in Sheet 660-1 and minimizes required wall height increases or channel banking.

2. Spiral Transitions. Spiral curves involve the solution of cubic equations by complex procedures, extensive successive approximation, or computers. The Los Angeles District (LAD) has prepared extensive spiral tables for easier manual design of rapid flow channels.[3] HDC 660-2 to 660-2/4 summarize these tables and illustrate their application to channel design.

3. The LAD spiral is a modification of Talbot's railroad spiral and consists of a series of compounded circular arcs of 12.5-ft lengths. The spiral has varying radii, decreasing in finite steps from the beginning of the spiral. The curve geometry, equations, and the definitions used to develop the LAD tables are given in Chart 660-2. Two equal spirals are shown, one upstream and one downstream of the circular curve. The central angle of the first arc (δ_1) establishes the shape of the spiral. The central angle subtended by a spiral of n number of arcs is given by:

$$\Delta s = n^2 \delta_1 \tag{1}$$

where

Δs = total central angle at the n^{th} arc of the spiral, sec

n = number of arc lengths of 12.5 ft each

δ_1 = central angle of the first arc, sec

4. Unbanked Curves. The minimum length of spiral recommended by Douma[4] for an unbanked curve is

$$L = 1.82 \frac{VW}{\sqrt{gy}} \tag{2}$$

where V and y are the velocity and flow depth, respectively, computed using a minimum resistance coefficient (Chart 631) and W is the water-surface width.

5. Banked Curves. The minimum spiral length recommended by Gildea and Wong[5] for banked curves is:

$$L = 30\Delta y \tag{3}$$

where Δy is the rise in water surface between the channel center line and the outside wall. Use of this criterion will not usually result in free drainage of a channel banked by rotating the invert about the center-line elevation.

6. Unequal Spirals. Unequal spiral lengths at the beginning and end of the circular curve may be required to meet special field conditions. The geometric relations between the spirals and the circular curve are given in Chart 660-2/1. With these relations determined, the design for each spiral proceeds as in the case of equal spirals.

7. Spiral Design Tables. The original LAD tables have been abridged and are presented in Chart 660-2/2. The chart should be adequate for design purposes and for preparation of contract drawings. Values of spiral lengths L, tangent distances X, and offsets Y are tabulated for n number of stations for 22 spirals. The method of computing values of X and Y, and the radius r of the central simple curve is given in reference 3. The curve number corresponds to the value of the first spiral arc angle δ_1, in sec, and indicates the rate of change in curvature. The minimum spiral length should be that which satisfies equation 2 (unbanked) or 3 (banked), provides optimum fit to local physical conditions, and is commensurate with economy of construction.

8. Application. The computation procedure for a banked invert curve with spiral transitions at each end is given in Chart 660-2/3. The final curve layout for the example is given in Chart 660-2/4. In cases of intermittent flow the banking may result in an undesirable pool of stagnant water along the inside wall. This can be avoided by selecting a longer downstream spiral. The length of this spiral is dependent upon the curve number selected and the number of spiral arc lengths required to attain a radius approximating that computed for the central curve. Twice the spiral length multiplied by the channel slope must equal or exceed the invert banking for free drainage.

9. Computer Program. A computer program for the design and field layout of the channel curve geometry is given in Appendix V of EM 1110-2-1601.[6]

10. References.

(1) U. S. Army Engineer District, Los Angeles, CE, Hydraulic Model Study, Los Angeles River Improvements, Whitsett Avenue to Tujunga Wash, July 1949.

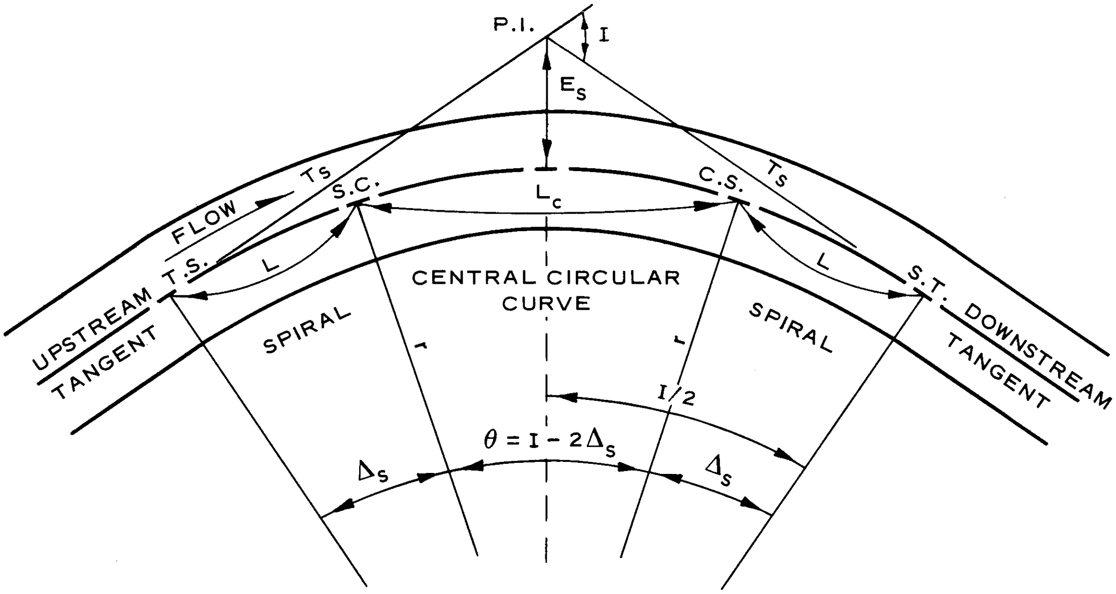
(2) Ippen, A. T., and Knapp, R. T., Experimental Investigations of Flow in Curved Channels. Reproduced by U. S. Army Engineer Office, Los Angeles, Calif. (2 volumes), 1958 (abstract of Results and Recommendations).

(3) U. S. Army Engineer District, Los Angeles, CE, Modified Spiral Curve Tables, June 1948.

(4) Douma, J. H., Discussion of "High-velocity flow in open channels; A symposium." Transactions, American Society of Civil Engineers, vol 116, paper 2434 (1951), pp 388-393.

(5) Gildea, A. P., and Wong, R. F., "Flood control channel hydraulics." Proceedings, Twelfth Congress of the International Association for Hydraulic Research, 11-14 September 1967, vol 1 (1967), pp 330-337.

(6) U. S. Army, Office, Chief of Engineers, "Appendix V: Computer program for designing banked curves for supercritical flow in rectangular channels," Engineering and Design; Hydraulic Design of Flood Control Channels. EM 1110-2-1601, Washington, D. C., 1 July 1970.



a. CHANNEL WITH SPIRAL CURVES

$$T_S = X - r\sin\Delta_S + (Y + r\cos\Delta_S)\tan\frac{I}{2}$$

$$E_S = \left[Y + r\sin\Delta_S \tan\left(\frac{I}{2} - \Delta_S\right)\right]\sec\frac{I}{2} + r\left[\sec\left(\frac{I}{2} - \Delta_S\right) - 1\right]$$

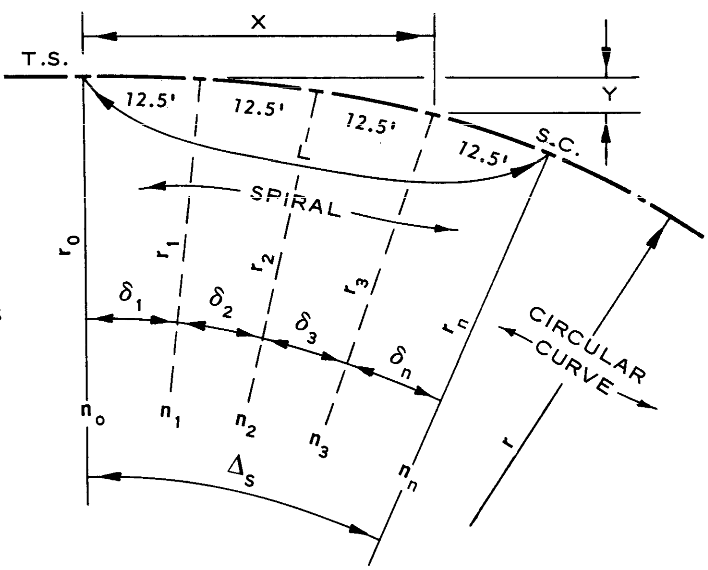
$$L_c = \frac{(I - 2\Delta_S)r}{57.2958}\ ;\ I,\ \Delta_S \text{ IN DEGREES}$$

$$\delta_n = (2n - 1)\delta_1$$

$$r_n = \frac{2{,}578{,}310.078}{\delta_n}$$

δ_1, δ_n IN SECONDS

$$\Delta_S = n^2\delta_1$$



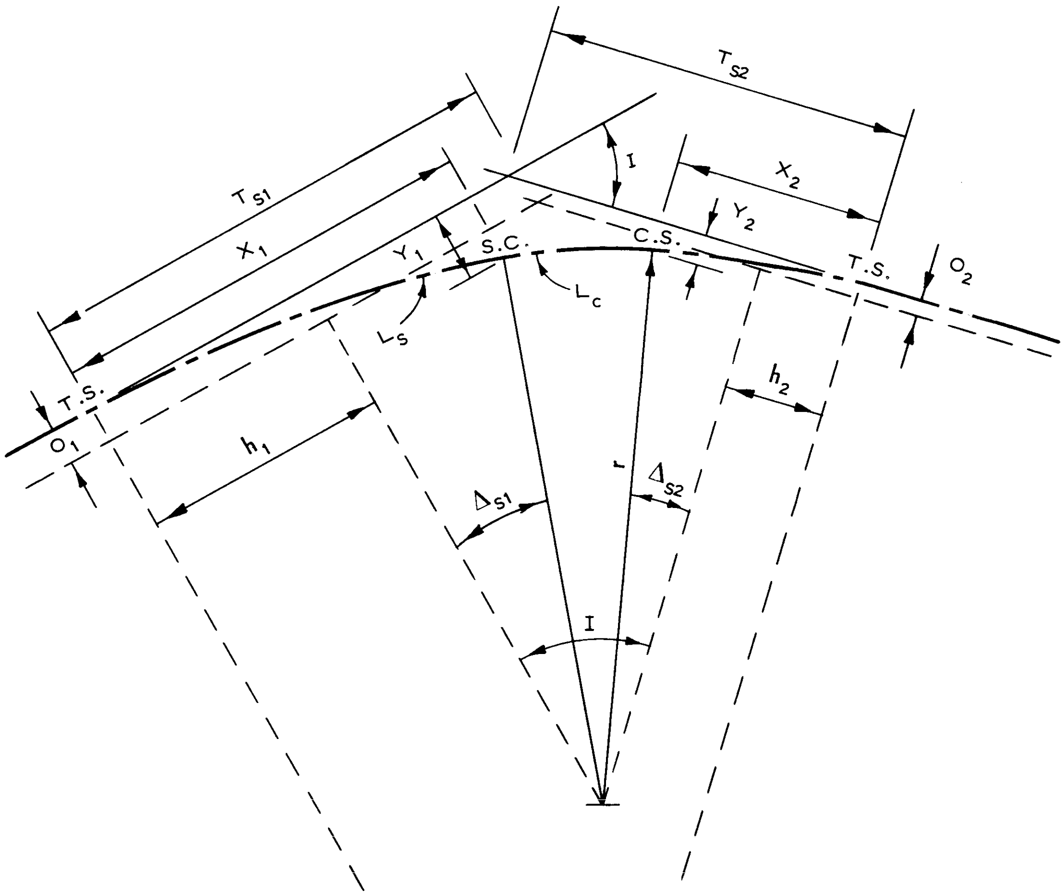
b. SPIRAL DETAILS

CHANNEL CURVE GEOMETRY
EQUAL SPIRALS

HYDRAULIC DESIGN CHART 660-2

PREPARED BY U. S. ARMY ENGINEER WATERWAYS EXPERIMENT STATION, VICKSBURG, MISSISSIPPI

WES 9-70



$$T_{S1} = \frac{(r + O_2) - (r + O_1)\cos I}{\sin I} + h_1$$

$$T_{S2} = \frac{(r + O_1) - (r + O_2)\cos I}{\sin I} + h_2$$

WHERE

$$h_1 = X_1 - r \sin \Delta_{S1}$$

$$h_2 = X_2 - r \sin \Delta_{S2}$$

$$O_1 = Y_1 - r(1 - \cos \Delta_{S1})$$

$$O_2 = Y_2 - r(1 - \cos \Delta_{S2})$$

NOTE: SEE CHART 660-2 FOR SPIRAL AND SIMPLE CURVE DETAILS

CHANNEL CURVE GEOMETRY

UNEQUAL SPIRALS

HYDRAULIC DESIGN CHART 660-2/1

No. 7 Curve

n	L, ft	r, ft	Δs ° ' "	X, ft	Y, ft
0	0.0		00 00 00		0.0
1	12.5		00 00 07	12.500	0.0
2	25.0	92,078	00 00 28	25.000	0.001
3	37.5	61,386	00 01 03	37.500	0.004
4	50.0	46,039	00 01 52	50.000	0.009
5	62.5	36,831	00 02 55	62.500	0.018
6	75.0	30,693	00 04 12	75.000	0.031
7	87.5	26,300	00 05 43	87.500	0.049
8	100.0	23,020	00 07 28	100.000	0.073
9	112.5	20,462	00 09 27	112.500	0.104
10	125.0	18,416	00 11 40	125.000	0.142
11	137.5	16,742	00 14 07	137.500	0.189
12	150.0	15,346	00 16 48	150.000	0.245
13	162.5	14,166	00 19 43	162.499	0.312
14	175.0	13,154	00 22 52	174.999	0.389
15	187.5	12,277	00 26 15	187.499	0.478
16	200.0	11,510	00 29 52	199.998	0.580
17	212.5	10,833	00 33 43	212.498	0.696
18	225.0	10,231	00 37 48	224.997	0.826
19	237.5	9,692	00 42 07	237.496	0.971
20	250.0	9,208	00 46 40	249.995	1.133
21	262.5	8,769	00 51 27	262.494	1.311
22	275.0	8,371	00 56 28	274.993	1.507
23	287.5	8,007	01 01 43	287.491	1.722
24	300.0	7,673	01 07 12	299.989	1.956
25	312.5	7,366	01 12 55	312.486	2.211
26	325.0	7,083	01 18 52	324.983	2.487
27	337.5	6,821	01 25 03	337.479	2.785
28	350.0	6,577	01 31 28	349.975	3.106
29	362.5	6,350	01 38 07	362.470	3.451
30	375.0	6,139	01 45 00	374.965	3.820
31	387.5	5,941	01 52 07	387.459	4.214
32	400.0	5,755	01 59 28	399.952	4.635

No. 10 Curve

n	L, ft	r, ft	Δs ° ' "	X, ft	Y, ft
0	0.0		00 00 00		0.0
1	12.5		00 00 10	12.500	0.0
2	25.0	64,450	00 00 40	25.000	0.002
3	37.5	42,966	00 01 30	37.500	0.006
4	50.0	32,225	00 02 40	50.000	0.013
5	62.5	25,780	00 04 10	62.500	0.026
6	75.0	21,483	00 06 00	75.000	0.044
7	87.5	18,414	00 08 10	87.500	0.070
8	100.0	16,112	00 10 40	100.000	0.104
9	112.5	14,322	00 13 30	112.500	0.148
10	125.0	12,890	00 16 40	125.000	0.203
11	137.5	11,718	00 20 10	137.500	0.270
12	150.0	10,742	00 24 00	149.999	0.350
13	162.5	9,915	00 28 10	162.499	0.445
14	175.0	9,207	00 32 40	174.998	0.556
15	187.5	8,593	00 37 30	187.498	0.683
16	200.0	8,056	00 42 40	199.997	0.829
17	212.5	7,582	00 48 10	212.496	0.994
18	225.0	7,161	00 54 00	224.994	1.180
19	237.5	6,784	01 00 10	237.493	1.387
20	250.0	6,445	01 06 40	249.991	1.618
21	262.5	6,138	01 13 30	262.488	1.873
22	275.0	5,859	01 20 40	274.985	2.153
23	287.5	5,604	01 28 10	287.481	2.460
24	300.0	5,371	01 36 00	299.977	2.795
25	312.5	5,156	01 44 10	312.471	3.159
26	325.0	4,958	01 52 40	324.965	3.553
27	337.5	4,774	02 01 30	337.458	3.979
28	350.0	4,604	02 10 40	349.949	4.437
29	362.5	4,445	02 20 10	362.440	4.929
30	375.0	4,297	02 30 00	374.929	5.456
31	387.5	4,158	02 40 10	387.416	6.020
32	400.0	4,028	02 50 40	399.901	6.621

No. 14 Curve

n	L, ft	r, ft	Δs ° ' "	X, ft	Y, ft
0	0.0		00 00 00		0.0
1	12.5		00 00 14	12.500	0.0
2	25.0	46,039	00 00 56	25.000	0.003
3	37.5	30,693	00 02 06	37.500	0.008
4	50.0	23,020	00 03 44	50.000	0.019
5	62.5	18,416	00 05 50	62.500	0.036
6	75.0	15,346	00 08 24	75.000	0.062
7	87.5	13,154	00 11 26	87.500	0.098
8	100.0	11,510	00 14 56	100.000	0.146
9	112.5	10,231	00 18 54	112.500	0.207
10	125.0	9,208	00 23 20	124.999	0.284
11	137.5	8,371	00 28 14	137.499	0.378
12	150.0	7,673	00 33 36	149.999	0.490
13	162.5	7,083	00 39 26	162.498	0.623
14	175.0	6,577	00 45 44	174.997	0.778
15	187.5	6,139	00 52 30	187.496	0.957
16	200.0	5,755	00 59 44	199.994	1.161
17	212.5	5,416	01 07 26	212.492	1.392
18	225.0	5,115	01 15 36	224.989	1.652
19	237.5	4,846	01 24 14	237.486	1.942
20	250.0	4,604	01 33 20	249.982	2.265
21	262.5	4,385	01 42 54	262.477	2.622
22	275.0	4,185	01 52 56	274.970	3.014
23	287.5	4,003	02 03 26	287.463	3.444
24	300.0	3,837	02 14 24	299.954	3.913
25	312.5	3,683	02 25 50	312.444	4.422
26	325.0	3,541	02 37 44	324.932	4.974
27	337.5	3,410	02 50 06	337.417	5.569
28	350.0	3,289	03 02 56	349.901	6.211
29	362.5	3,175	03 16 14	362.382	6.900
30	375.0	3,069	03 30 00	374.860	7.638
31	387.5	2,970	03 44 14	387.335	8.427
32	400.0	2,877	03 58 56	399.807	9.268

No. 18 Curve

n	L, ft	r, ft	Δs ° ' "	X, ft	Y, ft
0	0.0		00 00 00		0.0
1	12.5		00 00 18	12.500	0.001
2	25.0	35,810	00 01 12	25.000	0.003
3	37.5	23,873	00 02 42	37.500	0.010
4	50.0	17,905	00 04 48	50.000	0.024
5	62.5	14,324	00 07 30	62.500	0.046
6	75.0	11,937	00 10 48	75.000	0.080
7	87.5	10,231	00 14 42	87.500	0.126
8	100.0	8,952	00 19 12	100.000	0.188
9	112.5	7,958	00 24 18	112.499	0.267
10	125.0	7,162	00 30 00	124.999	0.365
11	137.5	6,511	00 36 18	137.498	0.486
12	150.0	5,968	00 43 12	149.998	0.631
13	162.5	5,509	00 50 42	162.496	0.801
14	175.0	5,116	00 58 48	174.995	1.000
15	187.5	4,775	01 07 30	187.493	1.230
16	200.0	4,476	01 16 48	199.990	1.492
17	212.5	4,213	01 26 42	212.487	1.789
18	225.0	3,979	01 37 12	224.982	2.124
19	237.5	3,769	01 48 18	237.476	2.497
20	250.0	3,581	02 00 00	249.970	2.912
21	262.5	3,410	02 12 18	262.461	3.371
22	275.0	3,255	02 25 12	274.951	3.875
23	287.5	3,114	02 38 42	287.439	4.428
24	300.0	2,984	02 52 48	299.924	5.030
25	312.5	2,865	03 07 30	312.407	5.685
26	325.0	2,755	03 22 48	324.887	6.394
27	337.5	2,653	03 38 42	337.363	7.160
28	350.0	2,558	03 55 12	349.836	7.984
29	362.5	2,470	04 12 18	362.305	8.870
30	375.0	2,387	04 30 00	374.769	9.819
31	387.5	2,310	04 48 18	387.228	10.833
32	400.0	2,238	05 07 12	399.681	11.914

CURVED CHANNELS
SPIRAL CURVE TABLES

HYDRAULIC DESIGN CHART 660-2/2
(SHEET 1 OF 5)

PREPARED BY U. S. ARMY ENGINEER WATERWAYS EXPERIMENT STATION, VICKSBURG, MISSISSIPPI

No. 23 Curve

n	L, ft	r, ft	Δs ° ' "	X, ft	Y, ft
0	0.0		00 00 00		0.0
1	12.5		00 00 23	12.500	0.001
2	25.0	28,024	00 01 32	25.000	0.004
3	37.5	18,683	00 03 27	37.500	0.013
4	50.0	14,012	00 06 08	50.000	0.031
5	62.5	11,210	00 09 35	62.500	0.059
6	75.0	9,341	00 13 48	75.000	0.102
7	87.5	8,007	00 18 47	87.500	0.161
8	100.0	7,006	00 24 32	100.000	0.240
9	112.5	6,228	00 31 03	112.499	0.341
10	125.0	5,605	00 38 20	124.998	0.467
11	137.5	5,095	00 46 23	137.498	0.621
12	150.0	4,671	00 55 12	149.996	0.806
13	162.5	4,311	01 04 47	162.494	1.024
14	175.0	4,003	01 15 08	174.992	1.278
15	187.5	3,737	01 26 15	187.488	1.572
16	200.0	3,503	01 38 08	199.984	1.907
17	212.5	3,297	01 50 47	212.478	2.286
18	225.0	3,114	02 04 12	224.971	2.714
19	237.5	2,950	02 18 23	237.462	3.191
20	250.0	2,802	02 33 20	249.950	3.721
21	262.5	2,669	02 49 03	262.437	4.307
22	275.0	2,548	03 05 32	274.920	4.951
23	287.5	2,437	03 22 47	287.400	5.657
24	300.0	2,335	03 40 48	299.876	6.427
25	312.5	2,242	03 59 35	312.348	7.263
26	325.0	2,156	04 19 08	324.815	8.169
27	337.5	2,076	04 39 27	337.277	9.147
28	350.0	2,002	05 00 32	349.733	10.200
29	362.5	1,933	05 22 23	362.181	11.331
30	375.0	1,868	05 45 00	374.622	12.543
31	387.5	1,808	06 08 23	387.055	13.837
32	400.0	1,752	06 32 32	399.479	15.218

No. 28 Curve

n	L, ft	r, ft	Δs ° ' "	X, ft	Y, ft
0	0.0		00 00 00		0.0
1	12.5		00 00 28	12.500	0.001
2	25.0	23,020	00 01 52	25.000	0.005
3	37.5	15,346	00 04 12	37.500	0.016
4	50.0	11,510	00 07 28	50.000	0.037
5	62.5	9,208	00 11 40	62.500	0.072
6	75.0	7,673	00 16 48	75.000	0.124
7	87.5	6,577	00 22 52	87.500	0.196
8	100.0	5,755	00 29 52	99.999	0.292
9	112.5	5,115	00 37 48	112.499	0.415
10	125.0	4,604	00 46 40	124.998	0.568
11	137.5	4,185	00 56 28	137.496	0.756
12	150.0	3,837	01 07 12	149.994	0.981
13	162.5	3,541	01 18 52	162.491	1.246
14	175.0	3,289	01 31 28	174.988	1.556
15	187.5	3,069	01 45 00	187.483	1.913
16	200.0	2,877	01 59 28	199.976	2.321
17	212.5	2,708	02 14 52	212.467	2.783
18	225.0	2,558	02 31 12	224.956	3.303
19	237.5	2,423	02 48 28	237.443	3.884
20	250.0	2,302	03 06 40	249.926	4.530
21	262.5	2,192	03 25 48	262.406	5.243
22	275.0	2,093	03 45 52	274.881	6.027
23	287.5	2,002	04 06 52	287.352	6.886
24	300.0	1,918	04 28 48	299.817	7.822
25	312.5	1,842	04 51 40	312.275	8.840
26	325.0	1,771	05 15 28	324.726	9.943
27	337.5	1,705	05 40 12	337.169	11.133
28	350.0	1,644	06 05 52	349.604	12.414
29	362.5	1,588	06 32 28	362.028	13.790
30	375.0	1,535	07 00 00	374.440	15.264
31	387.5	1,485	07 28 28	386.841	16.839
32	400.0	1,439	07 57 52	399.228	18.518

No. 35 Curve

n	L, ft	r, ft	Δs ° ' "	X, ft	Y, ft
0	0.0		00 00 00		0.0
1	12.5		00 00 35	12.500	0.001
2	25.0	18,417	00 02 20	25.000	0.006
3	37.5	12,278	00 05 15	37.500	0.020
4	50.0	9,209	00 09 20	50.000	0.047
5	62.5	7,367	00 14 35	62.500	0.090
6	75.0	6,139	00 21 00	75.000	0.155
7	87.5	5,262	00 28 35	87.499	0.245
8	100.0	4,604	00 37 20	99.999	0.365
9	112.5	4,093	00 47 15	112.498	0.519
10	125.0	3,683	00 58 20	124.996	0.711
11	137.5	3,349	01 10 35	137.494	0.945
12	150.0	3,070	01 24 00	149.991	1.226
13	162.5	2,833	01 38 35	162.487	1.558
14	175.0	2,631	01 54 20	174.981	1.945
15	187.5	2,456	02 11 15	187.473	2.391
16	200.0	2,302	02 29 20	199.962	2.901
17	212.5	2,167	02 48 35	212.449	3.479
18	225.0	2,046	03 09 00	224.932	4.129
19	237.5	1,939	03 30 35	237.411	4.855
20	250.0	1,842	03 53 20	249.885	5.661
21	262.5	1,754	04 17 15	262.353	6.553
22	275.0	1,674	04 42 20	274.814	7.532
23	287.5	1,601	05 08 35	287.268	8.605
24	300.0	1,535	05 36 00	299.713	9.776
25	312.5	1,473	06 04 35	312.148	11.047
26	325.0	1,417	06 34 20	324.572	12.424
27	337.5	1,364	07 05 15	336.984	13.911
28	350.0	1,316	07 37 20	349.381	15.511
29	362.5	1,270	08 10 35	361.762	17.229
30	375.0	1,228	08 45 00	374.126	19.068
31	387.5	1,188	09 20 35	386.470	21.034
32	400.0	1,151	09 57 20	398.794	23.129

No. 44 Curve

n	L, ft	r, ft	Δs ° ' "	X, ft	Y, ft
0	0.0		00 00 00		0.0
1	12.5		00 00 44	12.500	0.001
2	25.0	14,650	00 02 56	25.000	0.008
3	37.5	9,767	00 06 36	37.500	0.025
4	50.0	7,325	00 11 44	50.000	0.059
5	62.5	5,860	00 18 20	62.500	0.113
6	75.0	4,883	00 26 24	75.000	0.195
7	87.5	4,186	00 35 56	87.499	0.308
8	100.0	3,662	00 46 56	99.998	0.459
9	112.5	3,256	00 59 24	112.497	0.652
10	125.0	2,930	01 13 20	124.994	0.893
11	137.5	2,664	01 28 44	137.491	1.188
12	150.0	2,442	01 45 36	149.986	1.541
13	162.5	2,254	02 03 56	162.479	1.958
14	175.0	2,093	02 23 44	174.969	2.445
15	187.5	1,953	02 45 00	187.457	3.006
16	200.0	1,831	03 07 44	199.940	3.647
17	212.5	1,724	03 31 56	212.419	4.373
18	225.0	1,628	03 57 36	224.892	5.190
19	237.5	1,542	04 24 44	237.359	6.102
20	250.0	1,465	04 53 20	249.818	7.116
21	262.5	1,395	05 23 24	262.268	8.236
22	275.0	1,332	05 54 56	274.707	9.467
23	287.5	1,274	06 27 56	287.134	10.815
24	300.0	1,221	07 02 24	299.547	12.285
25	312.5	1,172	07 38 20	311.945	13.881
26	325.0	1,127	08 15 44	324.324	15.610
27	337.5	1,085	08 54 36	336.684	17.477
28	350.0	1,046	09 34 56	349.022	19.485
29	362.5	1,010	10 16 44	361.334	21.641
30	375.0	977	11 00 00	373.619	23.948
31	387.5	945	11 44 44	385.874	26.413
32	400.0	916	12 30 56	398.095	29.040

CURVED CHANNELS
SPIRAL CURVE TABLES

HYDRAULIC DESIGN CHART 660-2/2
(SHEET 2 OF 5)

No. 56 Curve

n	L, ft	r, ft	Δs ° ' "	X, ft	Y, ft
0	0.0		00 00 00		0.0
1	12.5		00 00 56	12.500	0.002
2	25.0	11,510	00 03 44	25.000	0.010
3	37.5	7,674	00 08 24	37.500	0.032
4	50.0	5,755	00 14 56	50.000	0.075
5	62.5	4,604	00 23 20	62.500	0.144
6	75.0	3,837	00 33 36	74.999	0.248
7	87.5	3,289	00 45 44	87.498	0.392
8	100.0	2,878	00 59 44	99.997	0.584
9	112.5	2,558	01 15 36	112.495	0.830
10	125.0	2,302	01 33 20	124.991	1.137
11	137.5	2,093	01 52 56	137.485	1.512
12	150.0	1,918	02 14 24	149.977	1.961
13	162.5	1,771	02 37 44	162.466	2.492
14	175.0	1,644	03 02 56	174.950	3.111
15	187.5	1,535	03 30 00	187.430	3.825
16	200.0	1,439	03 58 56	199.903	4.641
17	212.5	1,354	04 29 44	212.369	5.565
18	225.0	1,279	05 02 24	224.826	6.604
19	237.5	1,212	05 36 56	237.272	7.765
20	250.0	1,151	06 13 20	249.705	9.054
21	262.5	1,096	06 51 36	262.124	10.477
22	275.0	1,046	07 31 44	274.525	12.043
23	287.5	1,001	08 13 44	286.907	13.756
24	300.0	959	08 57 36	299.267	15.624
25	312.5	921	09 43 20	311.601	17.653
26	325.0	885	10 30 56	323.906	19.849
27	337.5	853	11 20 24	336.179	22.219
28	350.0	822	12 11 44	348.417	24.768
29	362.5	794	13 04 56	360.614	27.503
30	375.0	767	14 00 00	372.766	30.430
31	387.5	743	14 56 56	384.869	33.554
32	400.0	719	15 55 44	396.918	36.882

No. 71 Curve

n	L, ft	r, ft	Δs ° ' "	X, ft	Y, ft
0	0.0		00 00 00		0.0
1	12.5		00 01 11	12.500	0.002
2	25.0	9,079	00 04 44	25.000	0.013
3	37.5	6,052	00 10 39	37.500	0.041
4	50.0	4,539	00 18 56	50.000	0.095
5	62.5	3,631	00 29 35	62.500	0.183
6	75.0	3,026	00 42 36	74.999	0.314
7	87.5	2,594	00 57 59	87.498	0.497
8	100.0	2,270	01 15 44	99.995	0.740
9	112.5	2,017	01 35 51	112.491	1.052
10	125.0	1,816	01 58 20	124.985	1.441
11	137.5	1,651	02 23 11	137.476	1.917
12	150.0	1,513	02 50 24	149.963	2.487
13	162.5	1,397	03 19 59	162.445	3.160
14	175.0	1,297	03 51 56	174.920	3.944
15	187.5	1,210	04 26 15	187.387	4.849
16	200.0	1,135	05 02 56	199.844	5.883
17	212.5	1,068	05 41 59	212.289	7.054
18	225.0	1,009	06 23 24	224.720	8.370
19	237.5	956	07 07 11	237.133	9.840
20	250.0	908	07 53 20	249.526	11.473
21	262.5	865	08 41 51	261.895	13.276
22	275.0	825	09 32 44	274.237	15.257
23	287.5	789	10 25 59	286.547	17.426
24	300.0	757	11 21 36	298.822	19.789
25	312.5	726	12 19 35	311.056	22.354
26	325.0	698	13 19 56	323.243	25.129
27	337.5	672	14 22 39	335.380	28.123
28	350.0	648	15 27 44	347.458	31.341
29	362.5	626	16 35 11	359.472	34.792
30	375.0	605	17 45 00	371.415	38.481
31	387.5	586	18 57 11	383.279	42.417

No. 90 Curve

n	L, ft	r, ft	Δs ° ' "	X, ft	Y, ft
0	0.0		00 00 00		0.0
1	12.5		00 01 30	12.500	0.003
2	25.0	7,162	00 06 00	25.000	0.016
3	37.5	4,775	00 13 30	37.500	0.052
4	50.0	3,581	00 24 00	50.000	0.120
5	62.5	2,865	00 37 30	62.499	0.232
6	75.0	2,387	00 54 00	74.998	0.398
7	87.5	2,046	01 13 30	87.496	0.630
8	100.0	1,790	01 36 00	99.992	0.938
9	112.5	1,592	02 01 30	112.486	1.333
10	125.0	1,432	02 30 00	124.976	1.827
11	137.5	1,302	03 01 30	137.462	2.429
12	150.0	1,194	03 36 00	149.941	3.152
13	162.5	1,102	04 13 30	162.411	4.005
14	175.0	1,023	04 54 00	174.872	4.999
15	187.5	955	05 37 30	187.319	6.145
16	200.0	895	06 24 00	199.750	7.455
17	212.5	843	07 13 30	212.162	8.937
18	225.0	796	08 06 00	224.550	10.604
19	237.5	754	09 01 30	236.911	12.465
20	250.0	716	10 00 00	249.239	14.531
21	262.5	682	11 01 30	261.529	16.812
22	275.0	651	12 06 00	273.775	19.317
23	287.5	623	13 13 30	285.971	22.057
24	300.0	597	14 24 00	298.109	25.041
25	312.5	573	15 37 30	310.182	28.279
26	325.0	551	16 54 00	322.182	31.780
27	337.5	531	18 13 30	334.099	35.551
28	350.0	512	19 36 00	345.924	39.603

No. 113 Curve

n	L, ft	r, ft	Δs ° ' "	X, ft	Y, ft
0	0.0		00 00 00		0.0
1	12.5		00 01 53	12.500	0.003
2	25.0	5,704	00 07 32	25.000	0.021
3	37.5	3,803	00 16 57	37.500	0.065
4	50.0	2,852	00 30 08	50.000	0.151
5	62.5	2,282	00 47 05	62.499	0.291
6	75.0	1,901	01 07 48	74.997	0.500
7	87.5	1,630	01 32 17	87.494	0.791
8	100.0	1,426	02 00 32	99.988	1.178
9	112.5	1,268	02 32 33	112.478	1.674
10	125.0	1,141	03 08 20	124.962	2.294
11	137.5	1,037	03 47 53	137.439	3.050
12	150.0	951	04 31 12	149.906	3.956
13	162.5	878	05 18 17	162.360	5.027
14	175.0	815	06 09 08	174.798	6.274
15	187.5	761	07 03 45	187.215	7.713
16	200.0	713	08 02 08	199.606	9.355
17	212.5	671	09 04 17	211.967	11.214
18	225.0	634	10 10 12	224.291	13.303
19	237.5	600	11 19 53	236.571	15.635
20	250.0	570	12 33 20	248.801	18.222
21	262.5	543	13 50 33	260.970	21.076
22	275.0	519	15 11 32	273.071	24.209
23	287.5	496	16 36 17	285.092	27.633
24	300.0	475	18 04 48	297.024	31.359
25	312.5	456	19 37 05	308.853	35.397

CURVED CHANNELS
SPIRAL CURVE TABLES

HYDRAULIC DESIGN CHART 660-2/2
(SHEET 3 OF 5)

PREPARED BY U. S. ARMY ENGINEER WATERWAYS EXPERIMENT STATION, VICKSBURG, MISSISSIPPI

No. 139 Curve

n	L, ft	r, ft	Δs ° ' "	X, ft	Y, ft
0	0.0		00 00 00		0.0
1	12.5		00 02 19	12.500	0.004
2	25.0	4,637	00 09 16	25.000	0.025
3	37.5	3,092	00 20 51	37.500	0.080
4	50.0	2,319	00 37 04	49.999	0.185
5	62.5	1,855	00 57 55	62.498	0.358
6	75.0	1,546	01 23 24	74.996	0.615
7	87.5	1,325	01 53 31	87.490	0.973
8	100.0	1,159	02 28 16	99.981	1.449
9	112.5	1,031	03 07 39	112.466	2.059
10	125.0	927	03 51 40	124.943	2.821
11	137.5	843	04 40 19	137.408	3.751
12	150.0	773	05 33 36	149.858	4.866
13	162.5	713	06 31 31	162.289	6.181
14	175.0	662	07 34 04	174.694	7.715
15	187.5	618	08 41 15	187.068	9.482
16	200.0	580	09 53 04	199.404	11.499
17	212.5	546	11 09 31	211.694	13.782
18	225.0	515	12 30 36	223.928	16.345
19	237.5	488	13 56 19	236.096	19.205
20	250.0	464	15 26 40	248.187	22.375
21	262.5	442	17 01 39	260.188	25.869
22	275.0	422	18 41 16	272.086	29.702

No. 168 Curve

n	L, ft	r, ft	Δs ° ' "	X, ft	Y, ft
0	0.0		00 00 00		0.0
1	12.5		00 02 48	12.500	0.005
2	25.0	3,837	00 11 12	25.000	0.031
3	37.5	2,558	00 25 12	37.500	0.097
4	50.0	1,918	00 44 48	49.999	0.224
5	62.5	1,535	01 10 00	62.497	0.433
6	75.0	1,279	01 40 48	74.993	0.743
7	87.5	1,096	02 17 12	87.486	1.176
8	100.0	959	02 59 12	99.973	1.751
9	112.5	853	03 46 48	112.451	2.489
10	125.0	767	04 40 00	124.917	3.409
11	137.5	698	05 38 48	137.366	4.533
12	150.0	639	06 43 12	149.793	5.879
13	162.5	590	07 53 12	162.191	7.468
14	175.0	548	09 08 48	174.553	9.319
15	187.5	512	10 30 00	186.870	11.452
16	200.0	480	11 56 48	199.130	13.885
17	212.5	451	13 29 12	211.323	16.636
18	225.0	426	15 07 12	223.436	19.724
19	237.5	404	16 50 48	235.452	23.166
20	250.0	384	18 40 00	247.356	26.978

No. 200 Curve

n	L, ft	r, ft	Δs ° ' "	X, ft	Y, ft
0	0.0		00 00 00		0.0
1	12.5		00 03 20	12.500	0.006
2	25.0	3,223	00 13 20	25.000	0.036
3	37.5	2,149	00 30 00	37.500	0.115
4	50.0	1,611	00 53 20	49.999	0.267
5	62.5	1,289	01 23 20	62.496	0.515
6	75.0	1,074	02 00 00	74.991	0.885
7	87.5	921	02 43 20	87.480	1.400
8	100.0	806	03 33 20	99.961	2.084
9	112.5	716	04 30 00	112.430	2.962
10	125.0	645	05 33 20	124.882	4.058
11	137.5	586	06 43 20	137.310	5.394
12	150.0	537	08 00 00	149.707	6.996
13	162.5	496	09 23 20	162.063	8.885
14	175.0	460	10 53 20	174.367	11.086
15	187.5	430	12 30 00	186.607	13.619
16	200.0	403	14 13 20	198.769	16.508
17	212.5	379	16 03 20	210.834	19.772
18	225.0	358	18 00 00	222.786	23.432
19	237.5	339	20 03 20	234.602	27.507

No. 237 Curve

n	L, ft	r, ft	Δs ° ' "	X, ft	Y, ft
0	0.0		00 00 00		0.0
1	12.5		00 03 57	12.500	0.007
2	25.0	2,720	00 15 48	25.000	0.043
3	37.5	1,813	00 35 33	37.500	0.136
4	50.0	1,360	01 03 12	49.998	0.316
5	62.5	1,088	01 38 45	62.495	0.610
6	75.0	907	02 22 12	74.987	1.048
7	87.5	777	03 13 33	87.472	1.659
8	100.0	680	04 12 48	99.946	2.469
9	112.5	604	05 19 57	112.402	3.510
10	125.0	544	06 35 00	124.834	4.807
11	137.5	494	07 57 57	137.233	6.390
12	150.0	453	09 28 48	149.588	8.285
13	162.5	418	11 07 33	161.886	10.521
14	175.0	389	12 54 12	174.112	13.123
15	187.5	363	14 48 45	186.248	16.117
16	200.0	340	16 51 12	198.273	19.527
17	212.5	320	19 01 33	210.164	23.377

CURVED CHANNELS
SPIRAL CURVE TABLES

HYDRAULIC DESIGN CHART 660-2/2
(SHEET 4 OF 5)

PREPARED BY U. S. ARMY ENGINEER WATERWAYS EXPERIMENT STATION, VICKSBURG, MISSISSIPPI

WES 9-70

No. 280 Curve

n	L, ft	r, ft	Δs ° ' "	X, ft	Y, ft
0	0.0		00 00 00		0.0
1	12.5		00 04 40	12.500	0.008
2	25.0	2,302	00 18 40	25.000	0.051
3	37.5	1,535	00 42 00	37.499	0.161
4	50.0	1,151	01 14 40	49.998	0.373
5	62.5	921	01 56 40	62.493	0.721
6	75.0	767	02 48 00	74.982	1.238
7	87.5	658	03 48 40	87.461	1.959
8	100.0	576	04 58 40	99.924	2.917
9	112.5	512	06 18 00	112.363	4.145
10	125.0	460	07 46 40	124.769	5.677
11	137.5	419	09 24 40	137.128	7.545
12	150.0	384	11 12 00	149.426	9.781
13	162.5	354	13 08 40	161.644	12.417
14	175.0	329	15 14 40	173.762	15.482
15	187.5	307	17 30 00	185.754	19.005
16	200.0	288	19 54 40	197.593	23.013

No. 340 Curve

n	L, ft	r, ft	Δs ° ' "	X, ft	Y, ft
0	0.0		00 00 00		0.0
1	12.5		00 05 40	12.500	0.010
2	25.0	1,896	00 22 40	25.000	0.062
3	37.5	1,264	00 51 00	37.499	0.196
4	50.0	948	01 30 40	49.996	0.453
5	62.5	758	02 21 40	62.489	0.876
6	75.0	632	03 24 00	74.973	1.504
7	87.5	542	04 37 40	87.442	2.379
8	100.0	474	06 02 40	99.888	3.541
9	112.5	421	07 39 00	112.298	5.031
10	125.0	379	09 26 40	124.659	6.889
11	137.5	345	11 25 40	136.952	9.153
12	150.0	316	13 36 00	149.154	11.862
13	162.5	292	15 57 40	161.239	15.050
14	175.0	271	18 30 40	173.177	18.754

No. 420 Curve

n	L, ft	r, ft	Δs ° ' "	X, ft	Y, ft
0	0.0		00 00 00		0.0
1	12.5		00 07 00	12.500	0.013
2	25.0	1,535	00 28 00	25.000	0.076
3	37.5	1,023	01 03 00	37.499	0.242
4	50.0	767	01 52 00	49.995	0.560
5	62.5	614	02 55 00	62.483	1.082
6	75.0	512	04 12 00	74.959	1.857
7	87.5	438	05 43 00	87.412	2.938
8	100.0	384	07 28 00	99.829	4.373
9	112.5	341	09 27 00	112.192	6.211
10	125.0	307	11 40 00	124.480	8.501
11	137.5	279	14 07 00	136.664	11.290
12	150.0	256	16 48 00	148.711	14.621
13	162.5	236	19 43 00	160.580	18.537

No. 520 Curve

n	L, ft	r, ft	Δs ° ' "	X, ft	Y, ft
0	0.0		00 00 00		0.0
1	12.5		00 08 40	12.500	0.016
2	25.0	1,240	00 34 40	25.000	0.095
3	37.5	826	01 18 00	37.498	0.299
4	50.0	620	02 18 40	49.992	0.693
5	62.5	496	03 36 40	62.475	1.339
6	75.0	413	05 12 00	74.937	2.299
7	87.5	354	07 04 40	87.365	3.636
8	100.0	310	09 14 40	99.738	5.410
9	112.5	275	11 42 00	112.029	7.682
10	125.0	248	14 26 40	124.204	10.509
11	137.5	225	17 28 40	136.220	13.946

No. 720 Curve

n	L, ft	r, ft	Δs ° ' "	X, ft	Y, ft
0	0.0		00 00 00		0.0
1	12.5		00 12 00	12.500	0.022
2	25.0	895	00 48 00	24.999	0.131
3	37.5	597	01 48 00	37.496	0.414
4	50.0	448	03 12 00	49.984	0.960
5	62.5	358	05 00 00	62.451	1.853
6	75.0	298	07 12 00	74.880	3.182
7	87.5	256	09 48 00	87.241	5.029
8	100.0	224	12 48 00	99.498	7.478
9	112.5	199	16 12 00	111.598	10.607
10	125.0	179	20 00 00	123.477	14.490

No. 1080 Curve

n	L, ft	r, ft	Δs ° ' "	X, ft	Y, ft
0	0.0		00 00 00		0.0
1	12.5		00 18 00	12.500	0.033
2	25.0	597	01 12 00	24.999	0.196
3	37.5	398	02 42 00	37.491	0.622
4	50.0	298	04 48 00	49.964	1.439
5	62.5	239	07 30 00	62.391	2.778
6	75.0	199	10 48 00	74.730	4.766
7	87.5	171	14 42 00	86.919	7.524
8	100.0	149	19 12 00	98.873	11.167

CURVED CHANNELS
SPIRAL CURVE TABLES

HYDRAULIC DESIGN CHART 660-2/2
(SHEET 5 OF 5)

PREPARED BY U. S. ARMY ENGINEER WATERWAYS EXPERIMENT STATION, VICKSBURG, MISSISSIPPI

WES 9-70

GIVEN:

Design $Q = 15{,}000$ cfs
Channel width $W = 50$ ft
Invert slope $S = 0.005$
Curve deflection angle $I = 45$ deg
Channel shape - rectangular
Design controls - Sheets 631 to 631-2, par 7b(2)

	Capacity	Curve geometry
Equivalent roughness k_s	0.007 ft	0.002 ft
Depth y	11.26 ft	10.33 ft
Velocity V	26.65 fps	29.05 fps
Critical depth d_c	14.0 ft	14.0 ft
Froude No.	1.40	1.59

REQUIRED:

Spiral (minimum length) and simple curve (minimum radius) geometries with invert banking

COMPUTE:

a. Simple curve radius (min)

$$r_{min} = \frac{4V^2W}{gy} = \frac{4(29.05)^2(50)}{(32.2)(10.33)} = 507.42 \text{ ft} \quad \text{(Eq 2, Sheet 660-1)}$$

b. Approximate banking (Chart 660-1) = $2\Delta y$

$$\frac{r}{W} = \frac{507.42}{50} = 10.14$$

For $V = 29.05$ fps and $\frac{r}{W} = 10.14$; $\frac{\Delta y}{C} = 2.6$

$\Delta y = 2.6(0.5) = 1.3$ ft

c. Spiral length (min) L

$L = 30\Delta y = 30(1.3) = 39$ ft (Eq 3)

d. Spiral curve geometry

For $r_{min} \approx 507$ and $L \approx 39$ use spiral curve No. 520 (Chart 660-2/2, Sheet 5 of 5)

$\Delta_s = 02°18'40''$

n	ΣL (ft)	r (ft)	δ_n* ° ' ''	X (ft)	Y (ft)
1	12.5		00 08 40	12.500	0.016
2	25.0	1,240	00 26 00	25.000	0.095
3	37.5	826	00 43 20	37.498	0.299
4	50.0	620	01 00 40	49.992	0.693
			02 18 40		

* $\delta_n = (2n-1)\delta_1$ (Chart 660-2)

CHANNEL CURVE
EXAMPLE COMPUTATION

PREPARED BY U. S. ARMY ENGINEER WATERWAYS EXPERIMENT STATION, VICKSBURG, MISSISSIPPI

WES 9-70

e. Simple curve geometry (use $r = 620$ ft)

(1) Central angle θ (Chart 660-2)

$$\theta = I - 2\Delta_s = 45 - 2(02°18'40'')$$

$$= 45 - (04°37'20'') = 40°22'40''$$

(2) Curve length L_c (Chart 660-2)

$$L_c = \frac{(I - 2\Delta_s)r}{57.2958} = \frac{(40°22'40'')(620)}{57.2958}$$

$$= \frac{40.38\,(620)}{57.2958} = 436.95 \text{ ft}$$

f. Total curve length L_c

$$L_T = 2L + L_c = 2(50) + 436.95 = 536.95 \text{ ft}$$

g. Corrected invert banking $= 2\Delta y$

$$\frac{r}{W} = \frac{620}{50} = 12.40$$

For $V = 29.05$ fps and $\frac{r}{W} = 12.40$

$$\frac{\Delta y}{C} = 2.2 \quad \text{(Chart 660-1)}$$

$$\Delta y = 2.2C = 2.2(0.5) = 1.10 \text{ ft}$$

$$2\Delta y = 2.20 \text{ ft}$$

h. Maximum allowable Δy_{max}

$$2\Delta y_{max} = 0.18W = 0.18(50) = 9.0 \text{ ft} \quad \text{(Eq 3, Sheet 660-1)}$$

$$\Delta y_{max} = 4.5 \text{ ft} > \Delta y = 1.10 \text{ ft} \quad \text{(item g) OK}$$

i. Curve tangent distance T_s

$$T_s = X - r \sin \Delta_s + (Y + r \cos \Delta_s) \tan \frac{I}{2}$$

$$49.992 - 620 \sin(02°18'40'') + (0.693 + 620 \cos 02°18'40'') \tan 22°30'00''$$

$$49.992 - 620(0.04033) + [0.693 + 620(0.99919)]\ 0.41421$$

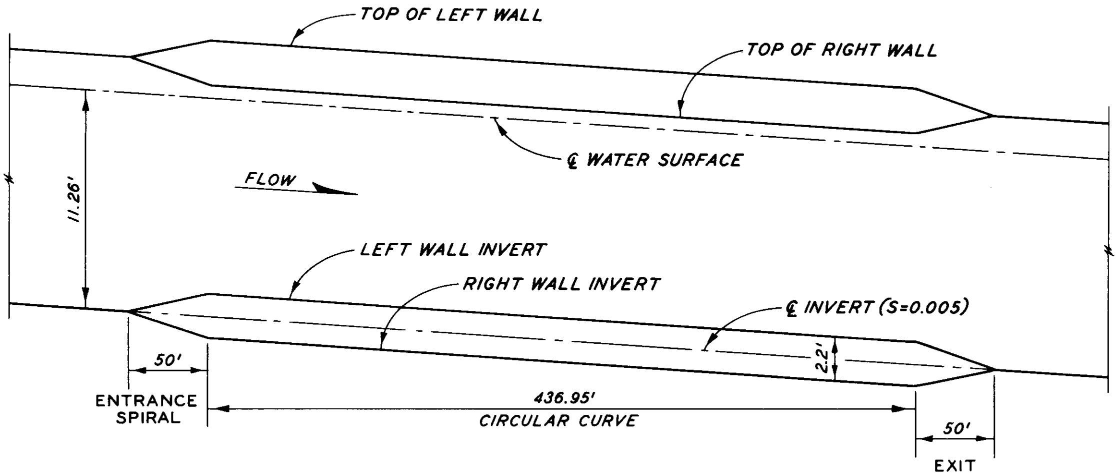
$$49.992 - 25.005 + (0.693 + 619.498)0.41421$$

$$24.987 + (620.191)0.41421 = 281.87 \text{ ft}$$

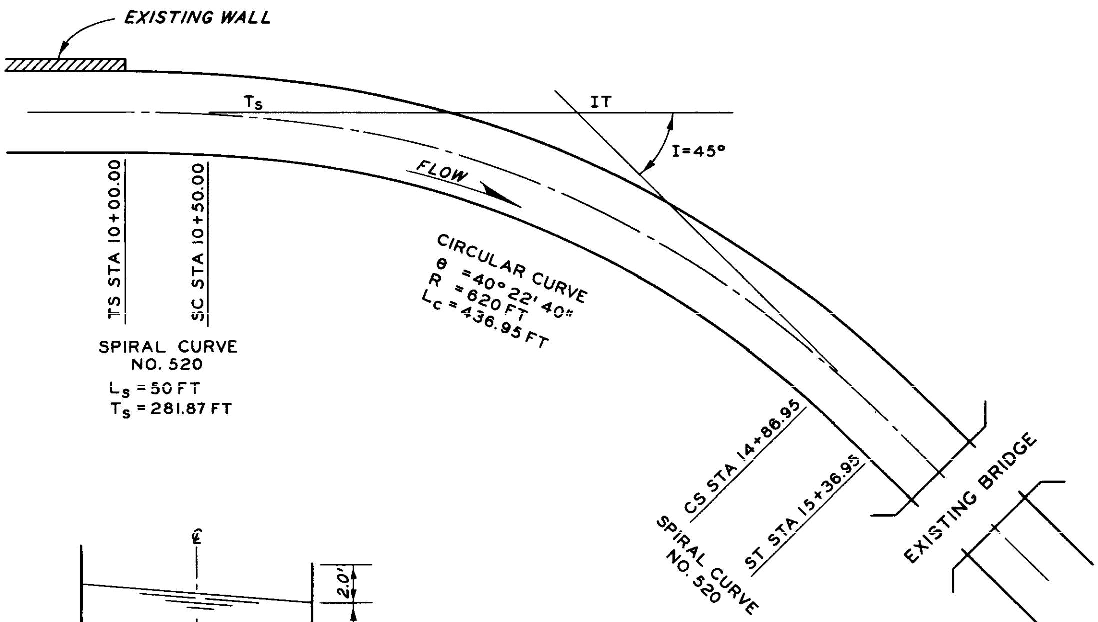
CHANNEL CURVE
EXAMPLE COMPUTATION

HYDRAULIC DESIGN CHART 660-2/3
(SHEET 2 OF 2)

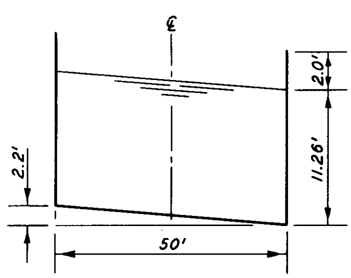
PREPARED BY U. S. ARMY ENGINEER WATERWAYS EXPERIMENT STATION, VICKSBURG, MISSISSIPPI



PROFILE



PLAN



CURVE SECTION

HYDRAULIC ELEMENTS – K=0.007 FT

STA TO STA		SECTION	SLOPE	Y_C, FT	V, FPS	Y, FT	F	Q, CFS
10+00	18+00	50' RECT	0.005	14.0	26.65	11.26	1.4	15,000

CURVED CHANNELS

EXAMPLE PLAN AND PROFILE

HYDRAULIC DESIGN CHART 660-2/4